9 Soil Conservation and Sediment Budgets

9.1 INTRODUCTION

Erosion is one of the most important and challenging problems for natural resource managers worldwide. It is the main source of sediment that pollutes streams and fills reservoirs. Some estimates of erosion rates in the 1970s were as high as 4 billion tons annually in the U.S. (Schwab et al., 1993). This amount dropped to 3 billion tons in 1982 and was estimated at 2.13 billion tons in 1993 due to advances in soil erosion control and a reduced number of acres under cultivation (NRCS, 1994).

In recent years, greater emphasis has been given to erosion as a contributor to *nonpoint pollution*. *Nonpoint* refers to pollution from the land surface rather than from industries, feedlots, or gullies. Eroded sediment can carry nutrients, particularly phosphates, to waterways and contribute to eutrophication of lakes and streams. Adsorbed pesticides are also carried with eroded sediments, lowering surface water quality.

Soil erosion can also reduce the productivity of some soils (Lowdermilk, 1953; Shertz et al., 1989). Eroded sediments remove soil organic matter, degrading soil structure and reducing its fertility. On shallow soils, the loss of topsoil can lead to reduced availability of soil water to plants, resulting in restricted growth because of drought stress (**Figure 9.1**).

The two major types of erosion are geological erosion and erosion from human or animal activities. Geological erosion includes soil-forming as well as soil-eroding processes that maintain the amount of soil in a favorable balance suitable for the growth of most plants. Geological erosion has contributed to the formation of our soils and caused many of our present topographic features, such as canyons, stream channels, and valleys. Conversely, human tillage and vegetation removal by humans (such as deforestation) and grazing animals may cause accelerated erosion, which leads to a loss of soil productivity.

Water erosion is the detachment and transport of soil from the land by water, including rainfall and runoff from melted snow and ice. Types of water erosion include interrill (raindrop and sheet), rill, gully, and stream channel erosion. Water erosion is accelerated by farming, forestry, grazing, and construction activities.

9.2 FACTORS AFFECTING EROSION BY WATER

The major variables affecting soil erosion are climate, soil, vegetation, and topography. Of these, vegetation and, to some extent, soil and topography may be controlled. Climatic factors, however, are beyond human control.

9.2.1 CLIMATE

Climatic factors affecting erosion are temperature, humidity, solar radiation, wind, and precipitation. Temperature, humidity, solar radiation, and wind are most evident through their effects on evaporation and transpiration.

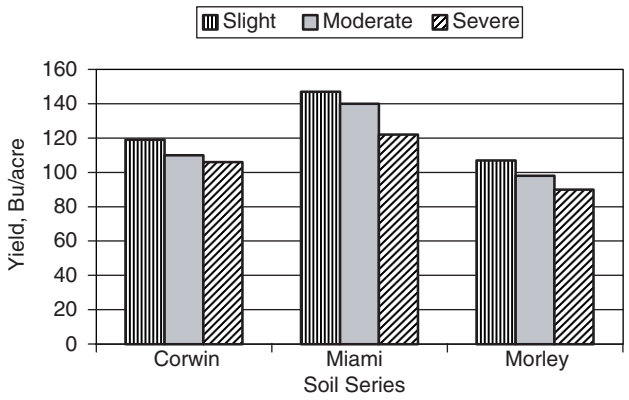

FIGURE 9.1 Effect of erosion phase and soil series on crop yield. (Based on data by Shertz et al. 1989.)

FIGURE 9.2 Mass wasting due to deforestation.

These processes reduce soil water content and subsequently decrease surface runoff rates and erosion. Wind also changes raindrop velocities and the angle of impact, which may influence erosion rates. The relationship among precipitation characteristics, runoff, and soil loss is complex; a more complete discussion is presented here.

9.2.2 Soil

Soil properties affect the infiltration capacity and the extent that soil particles can be detached and transported. For example, clay particles are more difficult to detach than sand, but clay is more easily transported. Texture is the dominant property determining erodibility, but soil structure, organic matter, water content, and density or compactness, as well as chemical and biological characteristics of the soil, also influence erodibility (Elliot et al., 1993).

9.2.3 Vegetation

Vegetation plays a major role in reducing erosion by (1) protecting the soil from raindrop impact; (2) reducing surface runoff velocity; (3) holding soil in place; (4) improving soil structure with roots, plant residue, and increased biological activity in the soil; and (5) increasing transpiration rates. These vegetative influences vary with the species, climate, season, soil type, and degree of maturity of the vegetation, as well as the type of vegetative residue left from the previous crop, like roots, stems, or leaves. A particular global concern is deforestation. Often, this occurs in areas with very high precipitation rates. Once the trees are removed, there is little to stabilize the soil, and these areas rapidly become degraded and unsuitable for plant growth. Erosion rates are high, and in steep, sloping areas, there are often slope failures due to mass wasting (**Figure 9.2**). During the last 30 to 40 years, a significant portion of the world's forest cover has been removed by human activities.

9.2.4 Topography

Topographic features that influence erosion are slope steepness, length, and shape. On steep slopes, runoff water is more erosive and can more easily transport detached sediment downslope. On longer slopes, an increased accumulation of overland flow results in increased rill erosion. Concave slopes, with less-steep slopes at the foot of the hill, are less erosive than convex slopes. The relationship of the upland slopes to channels in a watershed and the sediment transport capabilities and stability of the channel will also influence the total erosion within a watershed.

9.3 TYPES OF EROSION

9.3.1 Interrill Erosion

Interrill erosion includes raindrop splash and erosion from shallow overland flow (**Figure 9.3**). Splash erosion results from the impact of raindrops directly on soil particles or on thin water surfaces. Although the impact of raindrops on shallow water surfaces may not splash soil, it does increase turbulence, providing greater sediment-carrying capacity.

Early erosion studies found that tremendous quantities of soil are splashed into the air, most particles more than once. The amount of soil splashed into the air was found to be 50 to 90 times greater than the runoff losses. Splashed particles may move more than 2 ft in height and more than 5 ft laterally on level surfaces (Ellison, 1947).

If raindrops fall on crop residue or growing plants, the raindrop energy is absorbed, and soil splash is reduced. Raindrop impact on bare soil not only causes splash, but also leads to crusting and increased runoff (see Chapter 3). Raindrops detach the soil particles, and

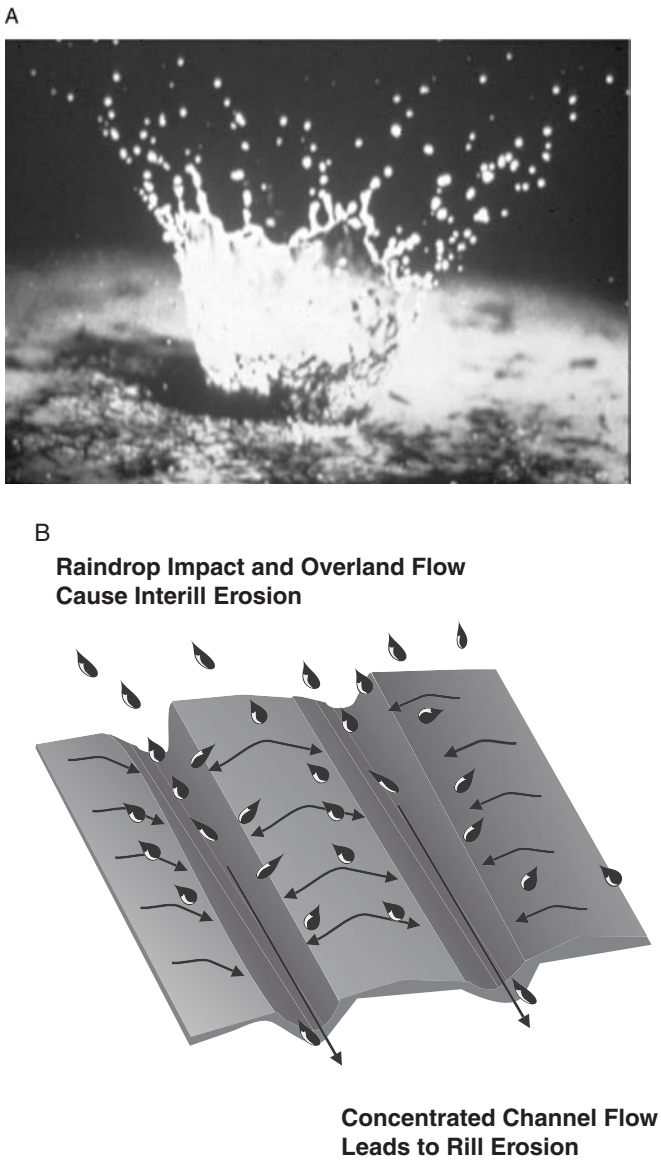

FIGURE 9.3 Predominant upland erosion processes: (A) splash erosion and (B) interrill and rill erosion.

the detached sediment can reduce the infiltration rate by sealing the soil pores. Shallow overland flow detaches some sediment, but mainly transports sediment first detached by raindrops. Low overland flow rates may result in reduced interrill erosion because of low sediment transport capacity. Research has shown interrill erosion is a function of soil properties, rainfall intensity, slope (Watson and Laflen, 1986; Liebenow et al., 1990), and in some cases, runoff rate (Kinnell and Cummings, 1993).

9.3.2 Rill Erosion

Rill erosion is the detachment and transport of soil by a concentrated flow of water. Rills are small enough to be removed by normal tillage operations (**Figure 9.3**B). Rill erosion depends on the runoff rate, which is affected by rainfall intensity, soil infiltration rates, and length of the slope contributing to overland flow.

Rill erosion is the dominant form of erosion on longer and steeper slopes, whereas interrill erosion is more dominant in shorter, flatter conditions. The interrill and rill erosion processes are incorporated in several physically based erosion prediction computer models, including the Water Erosion Prediction Project (WEPP) (L.J. Lane and Nearing, 1989).

9.3.3 Gully Erosion

Gully erosion produces channels larger than rills (**Figure 9.4**). These channels carry water during and

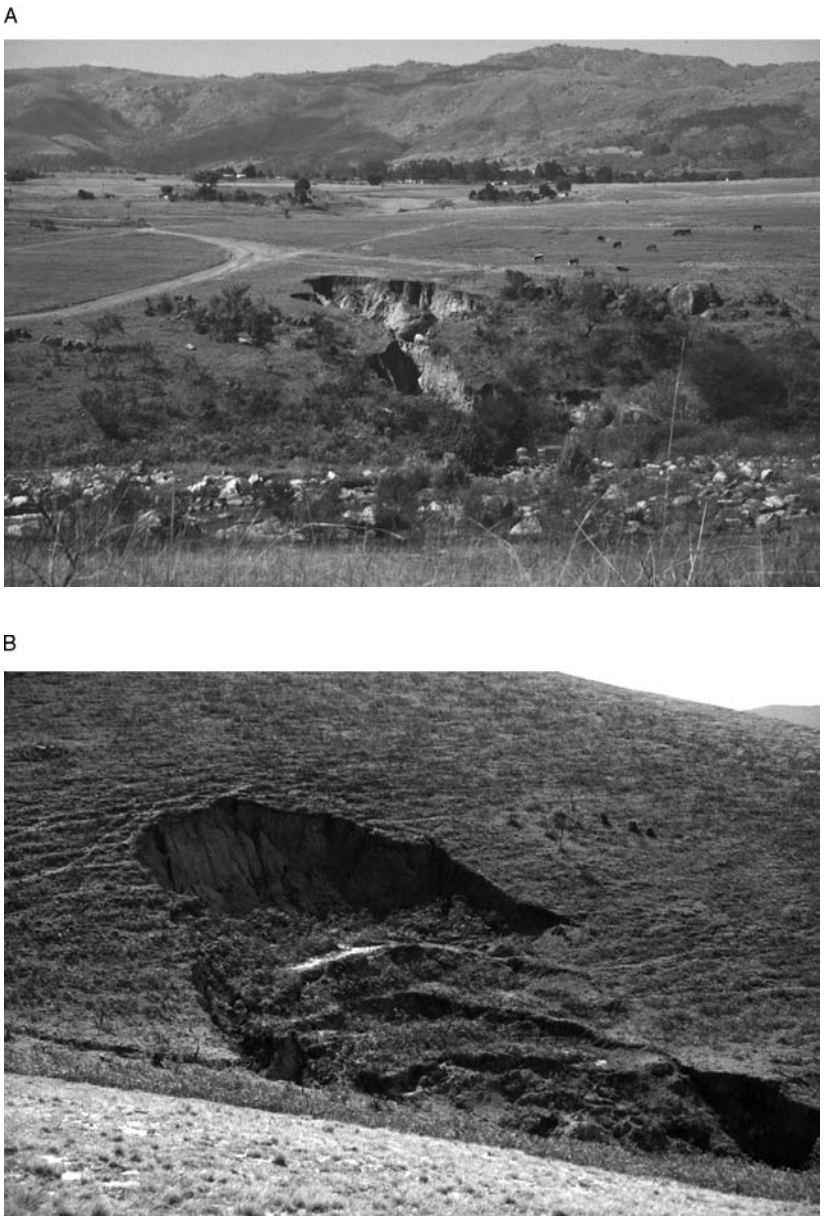

FIGURE 9.4 Gully erosion in Swaziland.

immediately after rains. Compared to rills, gullies cannot be obliterated by tillage. The amount of sediment from gully erosion is usually less than from rill and interrill erosion, but the nuisance from having fields divided by large gullies has been a greater problem.

The rate of gully erosion depends primarily on the runoff-producing characteristics of the watershed; the drainage area; soil characteristics; the alignment, size, and shape of the gully; and the slope in the channel (Bradford et al., 1973). Gully formation can be reduced or halted by diverting runoff away from the gully or by installing engineering structures at the head of the gully (Schwab et al., 1993).

9.3.4 Stream Channel Erosion

Stream channel erosion consists of soil removal from stream banks or soil movements in the channel (**Figure 9.5**). Stream banks erode by runoff flowing over the side of the stream bank, scouring and undercutting below the water surface, and mass wasting (failure) of the banks. Stream bank erosion, less serious than scour erosion, is often increased by the removal of vegetation, overgrazing, tilling too near the banks, or straightening the channel. Scour erosion is influenced by the velocity and direction of flow, depth and width of the channel, and soil texture. Poor

FIGURE 9.5 Stream channel erosion due to scour and bank instability.

channel alignment and the presence of obstructions such as sandbars increase meandering. Meandering is the major cause of erosion along the bank. Straightening channels, however, may increase the rate of scour erosion. Additional discussion is presented in Chapter 6 and Chapter 12.

9.4 ESTIMATING SOIL LOSSES

Soil losses, or relative erosion rates for different management systems, are estimated to assist farmers, natural resource managers, and government agencies in evaluating existing management systems or in future planning to minimize soil losses. In the period from 1945 to 1965, a method of estimating losses based on statistical analyses of small field plot data from many states was developed that resulted in the universal soil loss equation (USLE) (Wischmeier and Smith, 1978). A revised version of the USLE (RUSLE) has been developed for computer applications, allowing more detailed consideration of farming practices and topography for erosion prediction (Renard et al., 1991). The RUSLE program can be downloaded from http://www.sedlab.olemiss.edu/rusle/. A RUSLE2 version with a Windows interface is now under implementation and has greatly increased the capabilities of RUSLE; it can be obtained from http://bioengr.ag.utk.edu/rusle2/.

Since the mid-1960s, scientists have been developing process-based erosion computer programs that estimate soil loss by considering the processes of infiltration, runoff, detachment, transport, and deposition of sediment. Numerous research computer models have been developed, and some of these computer models are under improvement for field use. In the 1990s, it was anticipated that the process-based WEPP model would replace use of the USLE, particularly by the NRCS and other U.S. government agencies (G.R. Foster, 1988). However, a decade later, the RUSLE is still used extensively. The WEPP model with a Windows interface can be downloaded from: http://topsoil.nserl.purdue.edu/nserlweb/weppmain/wepp.html. This site also accesses an online version of the WEPP model with a simple interface that can be run from any computer with a Web browser. An interface similar to WEPP intended for forest and rangeland conditions can be found at http://forest.moscowfsl.wsu.edu/fswepp/.

9.5 THE UNIVERSAL SOIL LOSS EQUATION

The USLE continues to be a widely accepted method of estimating sediment loss despite its simplification of the many variables involved in soil loss prediction. It is useful for determining the adequacy of conservation measures in resource planning and for predicting nonpoint sediment losses in pollution control programs. The average annual soil loss, as determined by Wischmeier and Smith (1978), can be estimated from the equation

$$A = RKLSCP \tag{9.1}$$

where A is the average annual soil loss in tons/acre; R is the rainfall and runoff erosivity index for a geographic location; K is the soil erodibility factor; LS is the slope steepness and length factor; C is the cover management factor (**Table 9.1** or **Table 9.2**); and P is the conservation practice factor (**Table 9.3**).

In this text, English units are used for A, R, and K. If using other sources of information for the USLE, ensure that units are consistent (G.R. Foster et al., 1981). Although developed for use in the U.S., the procedure

TABLE 9.1
Cover Management *C* Factors for Permanent Pasture, Rangeland, and Idle Land[a]

Vegetal Canopy: Type and Height of Raised Canopy[b]	Canopy Cover[c]	Type[d]	Cover that Contacts the Surface: Percentage Ground Cover 0	20	40	60	80	95–100
No appreciable canopy		G	0.45	0.20	0.10	0.042	0.013	0.003
		W	0.45	0.24	0.15	0.090	0.043	0.011
Canopy of tall weeds or short brush	25	G	0.36	0.17	0.09	0.038	0.012	0.003
(1.5 ft fall height)[b]		W	0.36	0.20	0.13	0.082	0.041	0.011
	50	G	0.26	0.13	0.07	0.035	0.012	0.003
		W	0.26	0.16	0.11	0.075	0.039	0.011
	75	G	0.17	0.10	0.06	0.031	0.011	0.003
		W	0.17	0.12	0.09	0.067	0.038	0.011
Appreciable brush or bushes	25	G	0.40	0.18	0.09	0.040	0.013	0.003
(6 ft fall height)[b]		W	0.40	0.22	0.14	0.085	0.042	0.011
	50	G	0.34	0.16	0.85	0.038	0.012	0.003
		W	0.34	0.19	0.13	0.081	0.041	0.011
	75	G	0.28	0.14	0.08	0.036	0.012	0.003
		W	0.28	0.17	0.12	0.077	0.041	0.011
Trees, but no appreciable low brush	25	G	0.42	0.19	0.10	0.041	0.013	0.003
(12 ft. fall height)[b]		W	0.42	0.23	0.14	0.087	0.042	0.011
	50	G	0.39	0.18	0.09	0.040	0.013	0.003
		W	0.39	0.21	0.14	0.085	0.042	0.011
	75	G	0.36	0.17	0.09	0.039	0.012	0.003
		W	0.36	0.20	0.13	0.083	0.041	0.011

[a] All values shown assume (1) random distribution of mulch or vegetation and (2) mulch of appreciable depth where it exists.

[b] Average fall height of waterdrops from canopy to soil surface.

[c] Percentage of total area surface that would be hidden from view by canopy in a vertical projection.

[d] G = cover at surface is grass, grasslike plants, decaying compacted duff, or litter at least 2 in. deep; W = cover at surface is mostly broadleaf herbaceous plants (as weeds) with little lateral root network near the surface or undecayed residue.

Source: Cooperative Extension Service and Ohio State University, *Ohio Erosion Control and Sediment Pollution Abatement Guide*, Columbus, OH, 1979.

is used in many countries and has been the focus of considerable study during the past 30 years. Methods for determining each of the input parameters for the USLE and examples of their use follow.

9.5.1 Rainfall Erosivity *R*

The rainfall and runoff erosivity index *R* varies with amount of rainfall and individual storm precipitation patterns. For a given storm, a rainfall and runoff erosivity index *EI* is calculated. It is the product of the kinetic energy of the storm *E* and the maximum 30-min intensity for that storm *I*. An example calculation was presented in Chapter 2. The *EI* values for all the storms occurring in a given year for a location are summed to give an annual erosivity index. The average annual rainfall and runoff erosivity index *R* is shown in **Figure 9.6** for the continental U.S.

EXAMPLE 9.1

What is the *R* factor for a farm located in northeast Iowa?

Solution

From **Figure 9.6**, determine *R* for northeast Iowa.

Answer

R = 170.

For development projects or land uses that change throughout the year, it is sometimes desirable to determine the rainfall erosivity associated with different periods during the year. **Figure 9.6** shows the cumulative distribution of rainfall erosivity for different locations in the U.S.

TABLE 9.2
Example of Typical Cover Management *C* Factors Developed by State Agencies for the Ohio Climate and Vegetation Conditions

		Tillage	Practice	
Vegetation	**Autumn Conventional**	**Spring Conventional**	**Spring Conservation**	**No Till**
Agricultural Rotations				
Continuous corn (Co)	0.40	0.36	0.27	0.10
Corn and soybeans (Sb)	0.42	0.37	0.24	0.10
Two-year rotation with corn grown in Year 1 and soybeans and wheat in Year 2	0.30	0.28	0.24	0.10
Corn, corn, oats (O), meadow (M)	0.13	0.12	0.10	0.064
Corn, oats, meadow, meadow	0.055	0.050	0.033	0.033
Corn, corn, oats, meadow, meadow	0.11	0.094	0.082	0.052
Corn, soybeans, oats, meadow, meadow	0.13	0.12	0.082	0.052
Permanent Pasture				
Poor condition				0.04
Good condition				0.01

Source: Cooperative Extension Service and Ohio State University, *Ohio Erosion Control and Sediment Pollution Abatement Guide*, Columbus, OH, 1979.

Estimates of partial year erosivity can be determined by distributing the erosivity determined from **Figure 9.6** with the percentages obtained from **Figure 9.7**.

EXAMPLE 9.2

Determine the rainfall erosivity for northeast Iowa for the period April 1 to October 1.

Solution

In Example 1, we determined that the annual erosivity was 170. In **Figure 9.7**, the climate in Iowa is described by Curve A. On April 1, Curve A is at 4%, and on October 1, Curve A is at 90%. Therefore, the percentage erosivity that occurs during this period is 90 − 4 = 86%.

Answer

The erosivity that occurs between April 1 and October 1 in northeast Iowa is $R = 170 \times 0.86 = 146$.

9.5.2 Soil Erodibility *K*

The soil erodibility factor *K* (**Figure 9.8**) for a series of benchmark soils was obtained by direct soil loss measurements from fallow plots located in many U.S. states (**Figure 9.9**). Soils that have high silt contents tend to be the most erodible. The presence of organic matter, stronger subsoil structure, and greater permeabilities generally decrease erodibility. In RUSLE, *K* varies to account for seasonal variation in soil erodibility, with higher erodibility in the spring or after tillage.

Soil erodibility factors for the 10 most common soils in each state are presented in Appendix D. A consideration with using the information in Appendix D is that land use activities might change the soil structure or permeability of a soil. This is particularly true if the land is used for agricultural purposes or if it has been severely disturbed by construction activities. One soil type may exhibit a wide range of erodibility values, depending on textural, slope, compaction, management, and cultivation factors. These problems can be addressed by applying the nomograph presented in **Figure 9.8** to determine the erodibility of a given soil.

EXAMPLE 9.3

Determine the soil erodibility *K* for a soil with the following properties: 65% silt and very fine sand; 5% sand; 2.8% organic matter content (OM); a fine granular soil structure; and a slow-to-moderate permeability.

Solution

In **Figure 9.8**, enter the left graph at silt plus very fine sand = 65%, move right and intersect with 5% sand, move up to 2.8% organic matter, move right to soil structure = 2, move down to permeability = 4, and then move left to determine *K*.

Answer

$K = 0.31$.

TABLE 9.3
Conservation Practice Factor *P* for the Universal Soil Loss Equation

Farming Up and Down Slope		
All crops		$P = 1.0$
Contour Farming		
Land Slope Percentage	***Maximum Slope Length[a] (ft)***	***P factor***
1 to 2	400	0.6
3 to 5	300	0.5
6 to 8	200	0.5
9 to 12	120	0.6
13 to 16	80	0.7
17 to 20	60	0.8
Strip Cropping		
With grass and row crop		Contour $P \times 0.5$
With small grain and row crop		Contour $P \times 0.67$
Terraces		
Loss from crop		Same as Contouring *P*
Loss from terrace		
With graded channel outlet		Contour $P \times 0.2$
With underground outlet		Contour $P \times 0.1$
Subsurface Drainage		
		$P = 0.6$

[a] Maximum slope length for strip cropping can be twice that for contouring.

Source: Bengtson, R.L., and G. Sabbagh, *J. Soil Water Cons.*, 45:480–482, 1990; Wischmeier, W.H., and D.D. Smith, *Predicting Rainfall Erosion Losses — A Guide to Conservation Planning*. USDA Handbook 537, USDA–Science and Education Administration, Washington, DC, 1978.

9.5.3 Topographic Factor *LS*

The topographic factor *LS* adjusts the predicted erosion rates to give greater erosion rates on longer or steeper slopes and lower erosion rates on shorter or flatter slopes compared to a USLE "standard" slope of 9% and slope length of 72.6 ft. The erosion plot in **Figure 9.9** approximates these topographic conditions.

The slope length is measured from the point where surface flow originates (usually the top of the ridge) to the outlet channel or a point downslope where deposition begins. RUSLE considers nonuniform concave or convex slopes (Renard et al., 1991), as do most process-based erosion prediction programs. For the USLE, the *LS* factor can be determined from **Figure 9.10**.

EXAMPLE 9.4

Determine the *LS* factor for the field with a slope steepness of 4% and a slope length of 700 ft.

Solution

From **Figure 9.10**, enter the *x* axis at 700 ft. Move up until you intersect the 4% slope line. Move left to find the *LS* factor.

Answer

LS = 0.9.

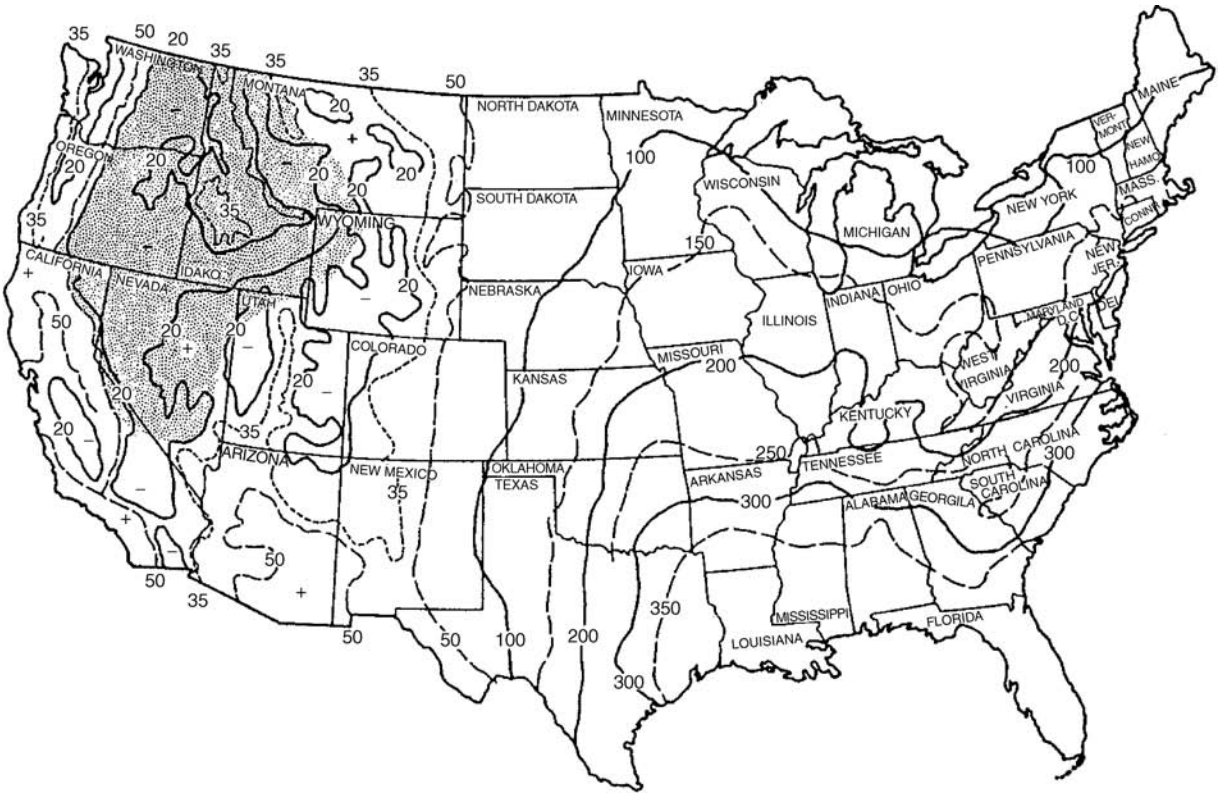

FIGURE 9.6 Rainfall and runoff erosivity index *R* distribution in the U.S. (From Wischmeier, W.H., and D.D. Smith, *Predicting Rainfall Erosion Losses — A Guide to Conservation Planning*. USDA Handbook 537, USDA–Science and Education Administration, Washington, DC, 1978.)

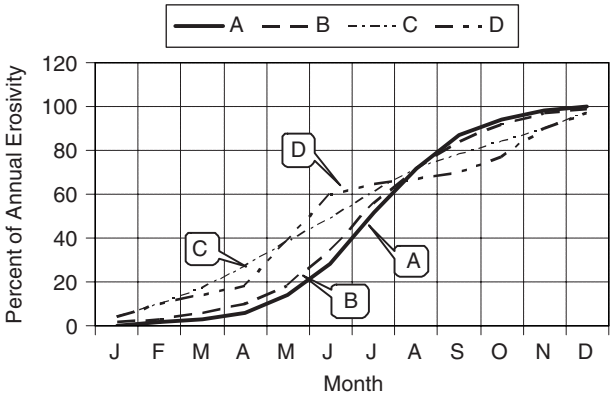

FIGURE 9.7 Monthly distribution of the rainfall erosivity index *R*. Curve A: Iowa, Nebraska, South Dakota; Curve B: Missouri, Illinois, Indiana, and Ohio; Curve C: Louisiana, Mississippi, Tennessee, and Arkansas; Curve D: Atlantic coastal plains of Georgia and the Carolinas. (Based on Wischmeier, W.H., and D.D. Smith, *Predicting Rainfall Erosion Losses — A Guide to Conservation Planning*. USDA Handbook 537, USDA–Science and Education Administration, Washington, DC, 1978.)

9.5.4 Cover Management Factor *C*

The cover management factor *C* includes the effects of vegetative cover, crop sequence, productivity level, length of growing season, tillage practices, residue management, and the expected time distribution of erosive events. For agricultural systems, *C* factors are generally based on crop rotations and tillage sequences. For forest, rangeland, and other nonagricultural conditions, *C* factors are generally estimated from the density of vegetation and the amount of vegetative residue on the soil surface.

Table 9.1 provides *C* factors that are useful for many different land uses in much of the U.S., provided the land use exhibits some vegetative cover. For a disturbed bare soil as in **Figure 9.10**, a value of 1.0 or greater should be used. The table is particularly valuable when relative soil losses associated with land use changes are determined. Erosion from permanent pasture, rangeland, and forest is generally much lower than from agricultural lands. Human or livestock activities, like roads, grazing, or timber harvest, that disturb the vegetation are generally the source of most of the eroded sediment from rangeland and forests. Forest erosion processes are discussed in detail in Chapter 10.

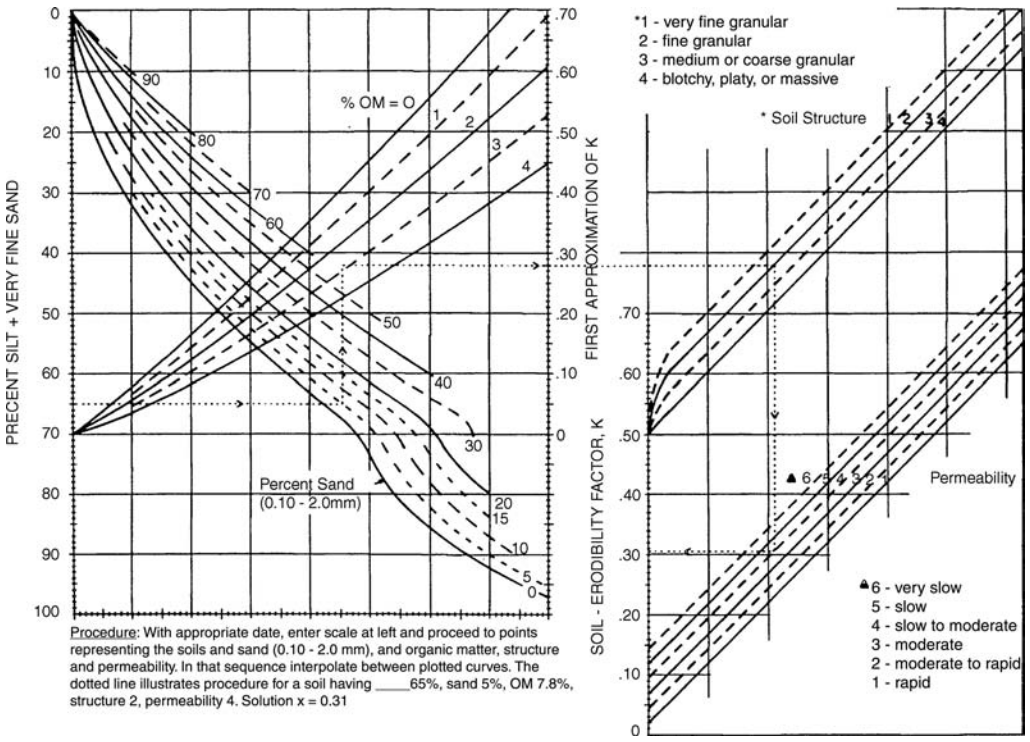
PRECENT SILT + VERY FINE SAND
% OM = O
Percent Sand
(0.10 - 2.0mm)
FIRST APPROXIMATION OF K
SOIL - ERODIBILITY FACTOR, K
*1 - very fine granular
2 - fine granular
3 - medium or coarse granular
4 - blotchy, platy, or massive
* Soil Structure
Permeability
6 - very slow
5 - slow
4 - slow to moderate
3 - moderate
2 - moderate to rapid
1 - rapid
Procedure: With appropriate date, enter scale at left and proceed to points representing the soils and sand (0.10 - 2.0 mm), and organic matter, structure and permeability. In that sequence interpolate between plotted curves. The dotted line illustrates procedure for a soil having ____65%, sand 5%, OM 7.8%, structure 2, permeability 4. Solution x = 0.31

FIGURE 9.8 Nomograph to determine soil erodibility *K* factor. (From Wischmeier, W.H., and D.D. Smith, *Predicting Rainfall Erosion Losses — A Guide to Conservation Planning*. USDA Handbook 537, USDA–Science and Education Administration, Washington, DC, 1978.)

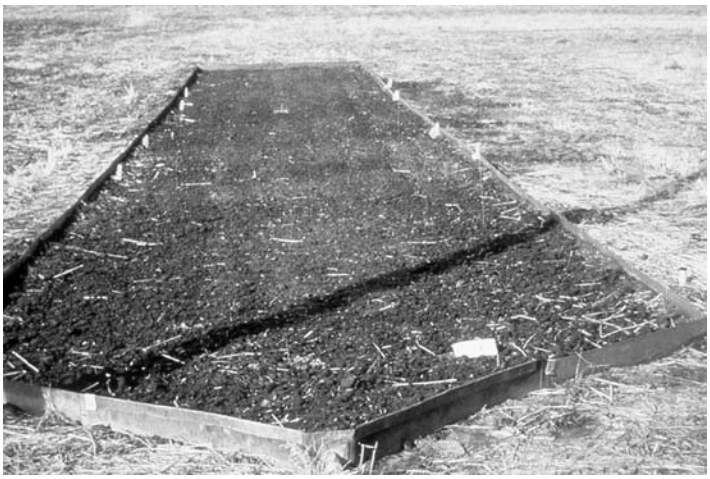

FIGURE 9.9 Fallow soil erosion plot located near Pullman, WA, with a standard length of 72.6 ft and a slope steepness of about 9%.

Example 9.5

Logging operations in Pennsylvania result in part of a forest being clear-cut. Immediately following the clear-cutting, there is no appreciable canopy, but there is a 40% ground cover of decaying compacted duff. A year after the clear-cutting, there is a 75% canopy of brush and short trees (4 to 8 ft high). Determine the change in the *C* factor during the first year following clear-cutting.

Solution

From **Table 9.1**, the *C* factor immediately following clear-cutting is 0.15. If we assume the percentage ground cover does not change during the first year, the *C* factor at the

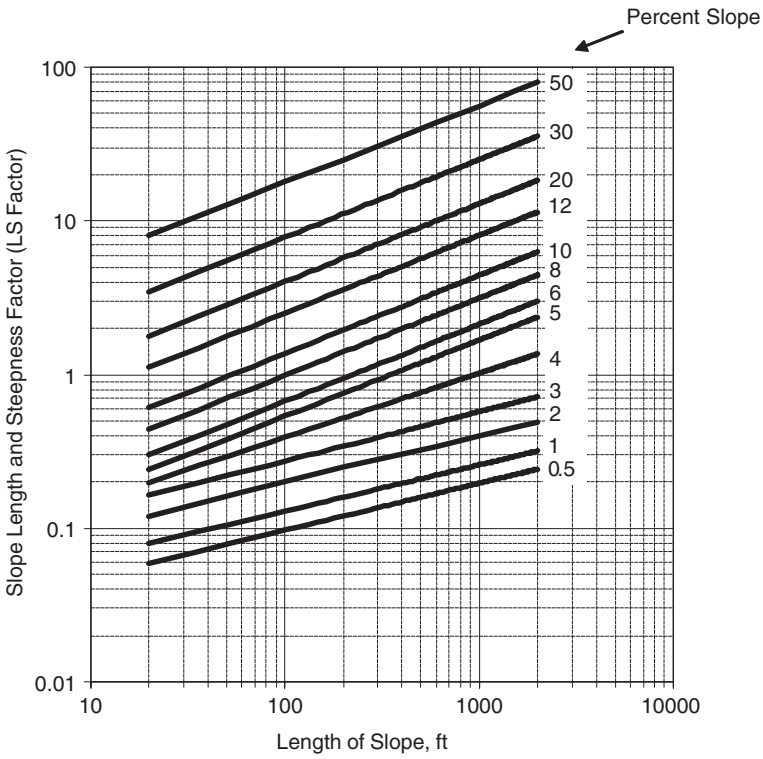

FIGURE 9.10 Slope and length factor *LS* as a function of slope and length.

end of this period will be 0.12. Therefore, based on the change in the *C* factor, soil losses at the end of the period will be 80% of that immediately following clear-cutting.

Answer

The change in canopy cover during the first year following clear-cutting will result in a 20% reduction in the *C* factor.

Table 9.2 gives some typical agricultural *C* factors for Ohio. These values should provide reasonable estimates for the central and eastern U.S. However, these factors do not account for climate differences between locations that might influence seasonal changes in *C* factors. Also, the table does not fully consider differences in the amount of residue left in a field following harvest. Whenever possible, you should consult local SCS or other natural resource agency offices to obtain *C* factors for your region.

From **Table 9.2**, it can be seen that the *C* factor will vary based on the crop and tillage practices. The traditional functions of tillage were weed control and preparation of a seedbed in which traditional planters and drills would function. With the development of conservation tillage planters and drills, tillage management has become increasingly important as a conservation tool. Currently, the primary purpose of tillage operations is to provide an adequate soil and water environment for the seedling to germinate. The role of tillage in weed control has diminished with increased use of herbicides and improved timing of operations.

Conventional tillage tends to incorporate the majority of surface residue, leaving the surface bare and susceptible to erosion. Conservation tillage systems leave residue from previous crops on the surface, protecting the soil from raindrop impact and reducing the erosive shear of sheet and rill flow on the soil. The presence of residue significantly reduces erosion rates, as can be seen by the lower *C* factors for all the conservation systems listed in **Table 9.2**.

One of the major benefits of reduced tillage is the increased amount of residue left on the surface, which reduces runoff and erosion. Other methods for reducing runoff, such as putting checks in furrows in cropland or imprinting rangeland, can also reduce erosion.

Example 9.6

As part of a conservation plan, a farmer in Indiana decided to place part of her land into pasture. Originally, the land was in continuous corn production, and the farmer used conventional tillage in the autumn. Determine the relative soil reduction associated with this land use change; assume the worst-case condition for pasture.

FIGURE 9.11 Contour strip cropping in Wisconsin.

Solution

From **Table 9.2**, it is determined that continuous corn production and conventional tillage in the autumn has a *C* factor of 0.40. The worst case for the pasture, poor condition, has a *C* factor of 0.04, which is 10% of 0.40.

Answer

Converting the land use into pasture will reduce soil loss by 90%.

9.5.5 Erosion Control Practice *P*

The vegetation cover or farming system selected can have a major effect on soil erosion rates. There are practices besides vegetation management that can be employed to control erosion. *Erosion control practices* include contouring, strip cropping, and terracing. For many applications, no erosion control practices will be used, and the *P* factor will be 1.0. **Table 9.3** presents typical *P* factors that can be used to estimate the effect of conservation practices on predicted soil erosion.

Contouring. *Contouring* or *contour farming* is conducting field operations, such as tillage, planting, and harvesting, approximately on the contour. Contouring reduces surface runoff by impounding water in small depressions and decreasing the development of rills. The greatest concentration of contouring in the U.S. is in the eastern wheat belt, where the benefits include both erosion reduction and conservation of water. The design of contours requires site surveying and is discussed in detail in the work of Schwab et al. (1993).

The relative effectiveness in reducing erosion by contouring on different slopes is shown by the conservation practice factor *P* in **Table 9.3**. The benefits of contouring decrease as the slope increases because the water-holding capacity of the rows diminishes with an increase in slope. Also, there are practical limitations on the slope length for which contouring is effective. On 2% slopes, the maximum slope length that should be contoured is about 400 ft, while for a 12% slope, the maximum length is only 120 ft. Contouring on steep slopes or under conditions of high rainfall intensity and soil erodibility will increase the risk of gullying because row breaks may release the stored water. Row breaks cause cumulative damage as the volume of water increases with each succeeding row.

Strip Cropping. *Strip cropping* is the practice of growing alternate strips of different crops in the same field. For controlling water erosion, the strips are on the contour (**Figure 9.11**). Rotations that provide strips of close-growing perennial grasses and legumes alternating with grain and row crops are the most effective practice to reduce erosion by water. Generally, strips that are farmed in row crops have parallel borders and widths that are convenient for multiple-row equipment operation. Maximum slope lengths for strip cropping can be twice those for contouring alone. For slope lengths longer than those recommended in **Table 9.3**, terracing is recommended if tillage operations are required for the management system.

The strips of grass or small grains act as sediment filters by slowing the overland flow velocity and increasing infiltration, causing sediment to be deposited. Also, the velocity of runoff entering the next strip of crop is reduced and therefore causes less soil erosion. The reason the grass strips act as filters is that they provide more near-surface vegetative cover than row crops such as the corn

FIGURE 9.12 Terraces on gradual sloping areas in Swaziland. Tall grass is planted on the terraces. Cattle in the foreground are a major cause of soil erosion as they compact the soil and remove vegetation.

or soybeans. A short-term economic impact of this practice is that some of the land is no longer in crop production or is planted to a crop such as grass, which has less economic value than corn or soybeans.

EXAMPLE 9.7

A farmer decides to switch from farming up and down the slope to contouring. The farmer's field has a slope of 3%. Determine the soil loss reduction benefit of this switch in practices. Also, determine any additional benefit that might be obtained if the farmer strip crops with grass.

Solution

From **Table 9.3**, a *P* factor of 0.5 is obtained for contouring on a 3% slope. Without contouring, the *P* factor would be 1.0. Therefore, contouring reduces the soil loss by 50%. Also, from **Table 9.3**, we see that strip cropping with grass will further reduce the *P* factor to 0.25. This will result in a 75% reduction ($1 - 0.25 \times 100$) in the predicted soil erosion. An additional reduction in erosion may also occur if the farmer has more years of grass (meadow) in the rotation because of a reduced *C* factor (**Table 9.2**).

Answer

A switch to contouring would reduce soil loss by 50%. Including strip cropping would reduce soil loss by 75%.

Terracing. A common erosion control practice is to construct terraces on eroding slopes (**Figure 9.12**). Terraces reduce the slope length and reduce runoff. The terrace channel may be level or graded to direct runoff to grassed waterways or subsurface drains that convey runoff away from the susceptible area. A level terrace restricts the lateral movement of water and is generally installed on soils with high infiltration rates or in drier climates for both soil and water conservation. The details of terrace design or construction are presented in the work of Schwab et al. (1993) and in other engineering textbooks.

Terracing affects the slope length so that the *LS* factor in a terracing system is altered to determine the amount of sediment delivered to the terrace. In terrace systems, the *P* factor can be used to estimate the reduction in sediment yield leaving the terrace. From **Table 9.3**, it is possible to predict either (1) sediment detached from the cropping area (the *P* factor is the same as for contouring) or (2) sediment yield leaving the field and include the terrace factor. The *P* factor for terrace sediment yield is 10 to 20% of the contour farming *P* factor.

EXAMPLE 9.8

For a field with a total slope length of 700 ft and an average steepness of 4%, find the *P* factor for (a) sediment delivered to terraces at 100-ft spacings and (b) sediment transported from a graded terrace channel with a spacing of 100 ft leading to a surface channel outlet.

Solution

Refer to **Table 9.3** to determine the appropriate *P* factors.

Answers

(a) For the sediment delivered to terraces at l00-ft spacings, *P* is the same as for the contour farming value, $P = 0.50$.

The slope length has been reduced from 700 to 100 ft, so from **Figure 9.10**, the *LS* factor will reduce from 0.9 to 0.5. (b) If the terraces have a graded channel to a surface drain, then the *P* factor for sediment delivery is $0.5 \times 0.2 = 0.1$.

9.6 SOIL LOSS TOLERANCE *T*

Natural resource managers sometimes find it helpful to determine a maximum level or tolerable level of erosion that can be allowed. Management plans can be evaluated by comparing the predicted erosion to a maximum or tolerable level. Both physical and economic factors, as well as social aspects, need to be considered in establishing soil loss tolerances, sometimes called *T* values. These values vary with topsoil depth and subsoil properties and range from 3 to 20 tons/acre. They are the maximum rates of soil erosion that will permit a high level of crop productivity to be sustained economically and indefinitely. In some cases, criteria for control of sediment pollution may dictate lower tolerance values. In other cases, it may be necessary to allow for higher levels of erosion to ensure the economic viability of a rural community.

9.7 APPLICATIONS OF THE UNIVERSAL SOIL LOSS EQUATION

In Section 9.5, we focused on determining the factors in the USLE and determining soil loss changes associated with each factor. Often, we will be interested in determining the soil loss associated with a combination of all or most of the factors. This will require knowledge of the location, soil, land use, slope steepness, slope length, and any erosion control practices. We present two examples of applying the USLE to estimate soil erosion. **Table 9.4** describes an actual field that had been experiencing severe erosion prior to the implementation of conservation practices.

TABLE 9.4
Details from a Field in Iowa with Observed Soil Erosion Susceptibility

Feature	Value
Location: Clayton County in northeast Iowa	
Soil series and texture: Kenyon loam	
Erodibility *K* factor	0.27
Stated *T* value	5 t/acres per year
Total length of slope	1200 ft
Length of eroding slope	720 ft
Average steepness of eroding slope	3%
Current farming system: contour strip cropping with grass, spring conventional tillage, 1.7 t/acre spring residue	
Rotation: corn, oats, meadow, meadow	

Source: USDA (1972).

EXAMPLE 9.9

Determine the average annual soil loss for the field described in **Table 9.4**.

Solution

From Example 9.1, $R = 170$. From **Table 9.4**, $K = 0.27$. From **Figure 9.6** for length = 720 ft and steepness = 3%, $LS = 0.6$. Assume Iowa *C* factors similar to Ohio, so from **Table 9.2** for Co O M M rotation, spring tillage, $C = 0.05$. From **Table 9.3** for contour strip cropping, $P = 0.5 \times 0.5 = 0.25$.

Answer

Applying Equation 9.1,

$$A = 170 \times 0.27 \times 0.6 \times 0.05 \times 0.25 = 0.34 \text{ tons/acre/year}$$

The erosion rate in Example 9.9 is relatively low for an agricultural system and is due to the combination of crop rotation and contour strip cropping, which are both very effective management techniques in reducing soil erosion. The *T* value for the field described in **Table 9.4** is 5 tons/acre/year. The above example predicts an erosion rate of less than 1 ton/acre/year, which will ensure that the productivity of that field is maintained indefinitely.

The USLE can be applied to many land uses, including agriculture, forests, pastures, rangeland, idle land, and land disturbances associated with surface mining or land development. However, when using the USLE, it is important to recognize that knowledge of *C* and *P* is better for agricultural applications than for surface mining or other land disturbances, such as urban development. Also, there is limited information available on *LS* factors for slopes greater than 20% or slope lengths greater than 2000 ft.

EXAMPLE 9.10

Compare annual soil losses prior to and following reclamation of a surface mining activity in eastern Kentucky. Disturbed areas are returned to the original contours, the average land slope is 20%, and typical slope lengths are 750 ft. Mining is conducted in a Shelocta soil series. Prior to mining, the area was predominantly a forest, and disturbed areas are undergoing reclamation to permanent

pasture. Poor soil fertility and acid conditions prevent establishment of more than 60% ground cover of grass and legumes in the pasture. Suggest conservation practices that might reduce the postmining soil losses to less than a soil loss tolerance T value of 5 tons/acre/year.

Solution

From **Figure 9.6**, determine that, for eastern Kentucky, the R factor is 150. From Appendix D, we find that a Shelocta soil has a K factor of 0.32. From **Figure 9.9**, establish that the LS factor for a 20% slope and a 750-ft slope length is 10. Using **Table 9.1**, the C factor for a forest is 0.003 (95 to 100% ground cover of decaying compacted duff), and the C factor for the permanent pasture will be about 0.042 (60% ground cover).

The only factor that changes when we move from the premining to postmining use is the C factor. The soil losses before and after reclamation are determined as:

Condition	*A*	*R*	*K*	*LS*	*C*	*P*
Premining forest	1.4	150	0.32	10	0.003	1.0
Postmining grass	20	150	0.32	10	0.042	1.0

It will be difficult to reduce postmining predicted losses from 20 to less than 5 tons/acre/year, but a number of options are available. Improved management to increase the vegetative cover will reduce the C factor. If soil fertility can be improved to give 80% cover rather than 60%, the C factor will decrease from 0.042 to 0.013. Installing terraces at 250-ft spacings will reduce the LS factor from 10 to 5.5. The following table summarizes the options:

Condition	*A*	*R*	*K*	*LS*	*C*	*P*
Postmining grass	20	150	0.32	10	0.042	1.0
Improved grass	6.24	150	0.32	10	0.013	1.0
Improved grass and terraces	3.4	150	0.32	5.5	0.013	1.0

Answer

To ensure that predicted postmining on-site erosion is reduced to less than 5 tons/acre/year, it is necessary to improve the soil fertility to ensure an 80% grass cover and to install terraces at 250-ft spacings.

In Example 9.10, if the proposed terraces drain into a grassed waterway, the sediment leaving the site will be reduced even further with a P factor of 0.2, leading to a predicted net soil loss from the site of 0.7 tons/acre/year. Natural resource managers need to determine if their goal is to reduce on-site erosion to maintain site productivity or to reduce off-site impacts to maintain water quality. See Chapter 14, Exercise 14.8, for additional examples of applications of the USLE.

9.8 DOWNSTREAM SEDIMENT YIELDS

Natural resource managers may need to know sediment delivery downstream in a watershed. One method for estimating sediment delivery is to use the USLE and a sediment delivery ratio (SDR). The USLE estimates gross sheet-and-rill erosion, but does not account for sediment deposited en route to the place of measurement or for gully or channel erosion downstream. The *sediment delivery ratio* is defined as the ratio of sediment delivered at a location in the stream system to the gross erosion from the drainage area above that point. This ratio varies widely with size of area, steepness, density of drainage network, and many other factors. For watersheds of 6.4, 320, 3,200, and 64,000 acres, ratios of 0.65, 0.33, 0.22, and 0.10, respectively, were suggested by Roehl (1962) as average values. The development of new process-based erosion models in GIS environments will enhance the prediction of sediment delivery from watersheds.

Renfro (1975), for the Blackland Prairie area in Texas, developed the SDR equation

$$\log_{10} SDR = 1.8768 - 0.14191 \log_{10} 10A \qquad (9.2)$$

where SDR is the sediment delivery ratio (percentage of annual erosion), and A is the drainage area in square miles ($A < 100$ mi^2).

Numerous other models have been developed. For example, the Soil and Water Assessment Tool (SWAT) (Arnold et al., 1996) considers storm runoff and uses the equation

$$SDR = \left[\left(\frac{q_p}{P_r} \right) \left(0.78285 + 0.21716 \frac{Q}{P} \right) \right]^{0.56} \qquad (9.3)$$

where SDR is the sediment delivery ratio (fraction of the gross erosion for the event), q_p is the peak runoff rate, P_r is the peak rainfall rate, P is the rainfall, and Q is the runoff depth (all units are millimeters or millimeters/hour, although inches and inches/hour can be used provided a consistent set of units is used for all quantities).

Example 9.11

Assume that the erosion rate calculated for the field in Example 9.9 is typical of a 320-acre watershed draining into a small reservoir. Estimate the sediment delivery to the reservoir for a 20-year period.

Solution

The average annual erosion rate is 0.34 tons/acre/year. The sediment delivery ratio for a 320-acre watershed was given as 0.33.

Answer

The sediment yield from 20 years will be

$$\text{Sediment} = 0.34 \text{ tons/acre/year} \times 320 \text{ acres} \times 20 \text{ years} \times 0.33 = 718 \text{ tons}$$

Exercise 14.8 in Chapter 14 has additional applications of predicting off-site impacts of soil erosion.

9.9 SINGLE-EVENT SEDIMENT YIELDS

The USLE is useful for determining gross erosion from an area for seasonal, annual, and extended time periods. In Section 9.8, we showed how a delivery ratio can be used to determine a downstream sediment yield estimate. However, application of a delivery ratio to gross erosion estimates based on the USLE cannot be used to obtain sediment yields for individual events, only for long-term averages. A method called the modified universal soil loss equation (MUSLE) (J.L. Williams, 1975) illustrates how sediment yields for individual storm events might be obtained:

$$Y = 95(Qq)^{0.56} K\,LS\,CP \tag{9.4}$$

where Y is the single-storm sediment yield in tons, Q is the storm runoff volume in acre-feet, q is the peak discharge in cubic feet/second, and the other terms are the standard USLE factors discussed in this chapter. The approach has seen widespread application, but should be used with caution as it was developed empirically based on limited data for Texas and the southwestern U.S. The procedure should only be used on small watersheds, and considerable judgment is required in selecting an appropriate slope length when determining the *LS* topographic factor. A delivery ratio should not be included if the sediment yield is determined at the outlet of the watershed used to obtain the runoff volume Q and the peak discharge q. However, if a sediment yield estimate is required downstream of the watershed evaluated with the MUSLE, then a delivery ratio would also need to be used. Estimates of Q and q can be obtained using the procedures presented in Chapter 5.

EXAMPLE 9.12

Determine the soil loss from the 320-acre watershed described in Examples 9.9 and 9.11 for a storm that produces 12 acre-ft of runoff and a peak discharge of 200 ft^3/sec from a 2-in. rainfall.

Solution

From Example 9.9, $K = 0.27$, $LS = 0.6$, $C = 0.05$, and $P = 0.25$.

$$Y = 95\,(12 \times 200)^{0.56}\,(0.27)(0.6)(0.05)(0.25) = 15 \text{ t}$$

Answer

The soil loss is 15 tons.

9.10 ESTIMATING SEASONAL *C* FACTORS FOR AGRICULTURAL CROPS

Sometimes, local C factors such as those presented in **Table 9.1** and **Table 9.2** are not available. This section demonstrates how to determine a C factor based on general crop properties (**Table 9.5**) in conjunction with a local climate (**Figure 9.4**).

Table 9.5 gives the seasonal losses from several typical farming systems as a percentage of the soil loss for continuous fallow soil during the growing season. The annual distribution of erosive events varies with geographic location. Examples from different regions of the U.S. are given in **Figure 9.7**. The C factor for a given crop rotation is found by first multiplying the soil loss ratio for each growth period in a crop rotation (**Table 9.5**) by the percentage of annual erosion during each respective period (**Figure 9.7**). These products are then summed, and an annual average is calculated to give the C factor (Example 9.13).

EXAMPLE 9.13

Calculate the C factor for the field described in **Table 9.4**.

Solution

Table 9.6 contains the solution to this example. The rotation given in **Table 9.4** is corn, oats or small grain, meadow, meadow.

1. The various stages of crop growth and their respective months are determined for each growth stage, and the months are entered in Column 1 of **Table 9.6**.

TABLE 9.5
Seasonal Distribution of Cover Management Factor Expressed as Percentage of Soil Loss from Crops to Corresponding Loss from Continuous Fallow for Selected Crop and Tillage Management Systems

Spring Planting				Soil Loss Ratio[a] for Crop Stage Period and Canopy Cover[b]						
Line no., Cover, Sequence and Management[c]	Residue[d] (tons)	Cover[e] (%)	F (%)	SB (%)	1 (%)	2 (%)	3:80 (%)	90 (%)	96 (%)	4L (%)
Continuous										
1 Co, RdL, spring, TP	2.3	—	31	55	48	38	—	—	20	23
2 As above, less residue										
6 Co, RdL, fall, TP	1.7	—	36	60	52	41	—	24	20	30
46 Co, chisel or cultivate only	GP	—	49	70	57	41	—	24	20	—
63 Co ridge tillage on contour	1.7	50	—	16	13	12	—	12	9	24
130 Small grain	—	—	—	0.7	0.7	0.7	0.7	0.7	0.7	0.7
200 Meadow	1.7	60	—	16	14	12	7	4	2	17
							0.8	0.6	0.4	
Rotation										
110 Co after Bn, spring conv	GP		47	78	65	51	—	30	25	37
124 Bn after Co, spring, TP	GP		39	64	56	41	—	21	18	22
210 Rowcrop after meadow, Rdl, spring, TP			9	24	21	18	—	12	10	18
Conservation Tillage										
52 Bn or Co after Co	1.3	40	—	21	20	19	19	15	12	30
121 Co after Bn	GP	30	—	33	29	25	22	18	14	33
131 Small grain after Co in disk residue	1.7	40	—	27	21	16	9	5	3	22

Bn = beans; Co = corn.

[a] The soil loss ratios, given as percentages of the loss that would occur from fallow, assume that the indicated crop sequence and practices are followed consistently.

[b] Crop stage periods are F, rough fallow; SB, seedbed until 10% canopy cover; 1, establishment until 50% canopy cover; 2, development until 75% canopy cover; 3, maturing until harvest for three different levels of canopy cover; 4L, residue or stubble.

[c] RdL, crop residue left in field; TP, plowed with moldboard.

[d] Dry mass per acre, after winter loss and reductions by grazing or partial removal, 2 t/acre represents a yield of 100 to 130 bu/acre; GP is good productivity level.

[e] Percentage of soil surface covered by plant residue mulch after crop seeding. The difference between spring residue and that on the surface after crop seeding is reflected in the soil loss ratios as residues mixed with the topsoil.

Source: Wischmeier, W.H., and D.D. Smith, *Predicting Rainfall Erosion Losses — A Guide to Conservation Planning*. USDA Handbook 537, USDA–Science and Education Administration, Washington, DC, 1978.

2. The *C* values from **Table 9.5** for each period are entered into **Table 9.6**, Column 2.
3. The percentage of annual erosivity for each of these periods is determined from **Figure 9.9**, Curve A, and entered into **Table 9.6**, Column 3.
4. The product of the *C* value and the erodibility (both expressed as decimal fractions) is calculated and entered in Column 4 of **Table 9.6**.
5. The sum of these products is divided by the number of years in the rotation to obtain an average *C* factor for the rotation, which is 0.060.

Answer

The *C* factor for the field described in **Table 9.4** is 0.060.

The calculated *C* factor of 0.06 from **Table 9.4** is greater than the *C* factor of 0.05 given in **Table 9.2** for Ohio conditions because the Iowa climate experiences more erosive storms during the critical crop period in June and July (compare the steepness of Curves A and B in **Figure 9.9**), and different assumptions may have been made regarding the *C* factor in the Ohio data.

TABLE 9.6
Solution to Example 9.13, Calculating the *C* Factor for the Conditions Described in Table 9.4

Months Column 1	Soil Loss, Percentage of Continuous Fallow (Table 9.5) Column 2	Annual Erosion (Figure 9.7) Percentage Column 3	*C* Factor Column 2 × Column 3 Column 4
Corn, First Year, Line 210			
January to April	0.6	10	0.0006
May	24	10	0.024
June	21	20	0.042
July	18	20	0.036
August to September	12	30	0.036
October to December	18	10	0.018
Small Grain with Meadow Seeding, Lines 130 and 200			
January to March	18	4	0.0072
April	16	6	0.0096
May	14	10	0.014
June	12	20	0.024
July to August	4	40	0.016
September to December	0.6	20	0.0012
Meadow, Line 200			
January to December	0.6	100	0.006
January to December	0.6	100	0.006
Total		400%	0.242
Average		0.242/4 =	0.060

9.11 SEDIMENT BUDGET CONCEPTS

9.11.1 Introduction

A particle of sediment often has a long and complicated journey on its way from upland slope to the sea (Walling, 1983). Both in the popular environmental literature (Gore, 1992) and, most egregiously, in the scientific literature (Pimentel et al., 1995), the idea remains that a particle of soil, once detached by running water, moves immediately on its way to the sea or to some navigable stream, lake, reservoir, or harbor, there to create havoc. The falseness of this idea is easily demonstrated. The most recent estimates of U.S. soil erosion are about 4 billion tonnes per year, but the sediment estimated to be leaving from rivers as sediment yield to the sea is only about 0.5 billion tonnes/year, of which a large, but unknown, quantity comes from stream channel and bank erosion (Meade et al., 1990; Trimble and Crosson, 2000). Part of the disparity of more than 3.5 billion tonnes/year is found in both large (Dendy and Champion, 1975; Meade et al., 1990) and small (Renwick, 1996; Smith, et al, 2002) reservoirs, which effectively trap much of the sediment transported by streams. Also, a large, but unknown, quantity is deposited in channels and on floodplains. The net result is that some of the missing 3.5 billion tonnes/year can be taken into account, but we simply do not know how much. Simply, there is no equilibrium or steady state between the slopes and the stream (Trimble, 1975a).

In Chapter 4, we looked at water budgets and saw that, for a given time period, all mass has to be taken into account. In that case, the input was precipitation, storage was in soil and groundwater, and outflow or efflux was *ET* and *Q* (Equation 4.4). Thus, if we know *P* and *Q* and can account for storage changes, we can calculate AET. A sediment budget is quite similar in that we must account for fluxes and storage of mass over time. The inputs are earth materials that come from slopes by erosion or mass movement (Toy et al., 2002). Additional sediment may come from wind erosion in some regions, as discussed in the first part of this chapter. Efflux is measured as sediment yield at some downstream point. Between the slopes and the downstream point where sediment yield is measured, however, there are many places along streams where sediment can be stored by stream or fluvial processes, thus decreasing downstream sediment yield. Likewise, fluvial processes may remove sediment from these same storage

"compartments" and release it downstream to become sediment yield. As we shall see, these fluxes and processes are quite complex, and the science of sediment budgets is in its infancy.

9.11.2 Sediment Delivery from Slopes

In the beginning of this chapter, we examined principles and prediction of soil erosion and pointed out that most sediment from eroded soil travels only a short distance downslope, and generally, only a small proportion actually moves into streams under ordinary conditions. Indeed, much of the eroded soil moves only a short distance and is deposited as slope deposits or colluvium. By practice. we adjust for this assumed deposition along the pathway using the SDR, the proportion of eroded soil reaching some point downstream (see Section 9.8 and Exercise 14.6, Chapter 14). But, we must understand that the SDR is a gross generalization based on few and very difficult to obtain data (Roehl, 1962; Walling, 1983); like most models, it can hide huge disparities. We have already discussed the efficiency of water moving in channels compared to that moving across slopes as shallow flow; so it is with sediment delivery from slopes to streams. If soil erosion is so advanced on an upland surface that rills and gullies are present, then water and sediment can be efficiently conveyed off the slopes; indeed, additional sediment may well come from the rills and gullies themselves. During the 1930s, when erosion was rampant on the Driftless Area (Mississippi River hill country or Paleozoic plateau), sediment delivery ratios were about 1.28 (Trimble and Lund, 1982). **Figure 9.13**A clearly demonstrates what was happening: The drainage density had radically increased under conditions of poor land use (1853 to 1935), so that rills and gullies could efficiently convey water and sediment to tributary streams. By the 1960s, when the landscape had been totally transformed by modern soil and water conservation practices (**Figure 9.13**B), there was no sign of rills and gullies, and not only had soil erosion been drastically reduced, but SDRs were also drastically reduced, averaging only 8%, with the disparity deposited as colluvium or alluvium (Trimble and Lund, 1982). Such are the vagaries and unknowns of moving sediment just a few hundred meters.

9.11.3 Sediment in Streams

Once the sediment moves into the stream system, the processes are even more complex (**Figure 9.14**). The first principle is that streams can transport only so much sediment over time (termed *capacity)*. A stream channel may be a fairly efficient conveyor of water and sediment, but during out-of-bank flows, much of the conveyance path is the floodplain. It is usually rough hydraulically and thus inefficient at routing sediment, especially through the lower main valley. The quite obvious result is that floodplains are subject to varying amounts of sediment storage as vertical accretion. Particularly under conditions of accelerated soil erosion, the amount of sediment conveyed exceeds the conveyance capacity of the floodway (channel and floodplain), so that the surplus is stored. This is clearly demonstrated by three sediment budgets for Coon Creek, Wisconsin, 1853 to 1993 (**Figure 9.14**). Perhaps the most noteworthy phenomenon is that, although sediment fluxes varied greatly through time, the flow of sediment yield out of the basin and into the Mississippi River remained approximately constant, demonstrating the sediment-trapping effect of stream floodplains, especially the wide floodplain of the lower main valley.

Conversely, when the stream is deprived of its "normal" load of sediment, the available stream energy may be used to erode the channel and banks. This is easily demonstrated in erodible channel reaches downstream of reservoirs. There, the reservoirs have trapped most of the sediment, creating flow with excess energy or "hungry water." Many such reaches have degraded several meters, and the eroded materials have been transported downstream as sediment yield (G.P. Williams and Wolman, 1984). Sometimes, the stream is unable to erode the channel bed (e.g., "armored" with large particles) or banks (e.g., armored with effective vegetation or riprap), so that its energy will simply be dissipated, and little work will be done.

Some of these concepts are embodied in **Figure 9.15**. Line BA, extended, is the steady state at which downstream sediment yield equals upstream sediment supply. Point and Level A is the maximum sediment conveyance capacity of the floodway. When upstream sediment supply exceeds A, the excess goes into storage, largely as vertical accretion on floodplains or channel filling. When upstream sediment supply drops below A, the stream attempts to use its excess energy to obtain sediment load from bed and banks. If sediment is easily obtainable and can be mobilized, it will be taken from storage; the perfect case is line AB′, with 100% of the available energy used for geomorphic work. However, in many cases, the bed and bank materials may be (1) too large to transport, (2) armored or protected by large particles or vegetation, or (3) to a much lesser extent, without sediment. The result of any and all of these cases is to make the stream dissipate at least part of its available energy. The latter condition, as we shall see, is what stream engineers and planners attempt to accomplish with bank reshaping, riprap, and vegetation.

9.11.4 The Southern Piedmont

These concepts are best demonstrated with examples from the American landscape. The southern Piedmont is a region that suffered massive historical soil erosion, but was reclaimed by soil conservation measures and reforestation

FIGURE 9.13 Hydrologic processes written on the landscape, Coon Creek, Wisconsin, basin, 1934 and 1967: A. Early 1934; note rectangular fields and gully systems extending into the upland agricultural fields. B. 1967; note contoured and strip cropped fields. Although the visible conservation methods here are striking, those not seen, such as crop rotations and stubble mulching, have just as much impact. (From Trimble, S.W., and S.W. Lund, Soil Conservation and the Reduction of Erosion and Sedimentation in the Coon Creek Basin, Wisconsin, USGS Professional Paper 1234, 1982.)

starting in the 1930s. The landscape changes and stream responses are shown over time in block diagrams indicating an upstream reach and a downstream reach (**Figure 9.16**). In **Figure 9.16**A, we see the heavily forested Piedmont at the time of European settlement (ca. 1770 to 1820). Settlers quickly took up the fertile floodplains and stream terraces for agriculture and for home sites. With time, the uplands were cleared for tobacco, corn, and cotton. The clean-tilled crops in this region of high *R* values (Koeppen Cfa, Chapter 2 and the USLE equation in this chapter) and often-steep slopes, along with poor soil conservation practices, created massive sheet and gully erosion that filled upstream valleys and moved progressively downstream (**Figure 9.16**B). Channels were to a large extent filled with sandy sediment, from the acid igneous soils, and this resulted in the raising of the stream levels. Natural levees formed, which then prevented water from moving to the stream, and the floodplains and low terraces became swamps.

The advent of soil conservation practices and reforestation in the 1930s greatly curtailed upland erosion, so runoff from the uplands no longer transported much sediment (for an analysis of the hydrology during this period, see A.P. Price, 1998). The result was as described in Section 9.11.3; that is, the hungry water eroded upstream channels, transporting the sediment downstream, where it exacerbated

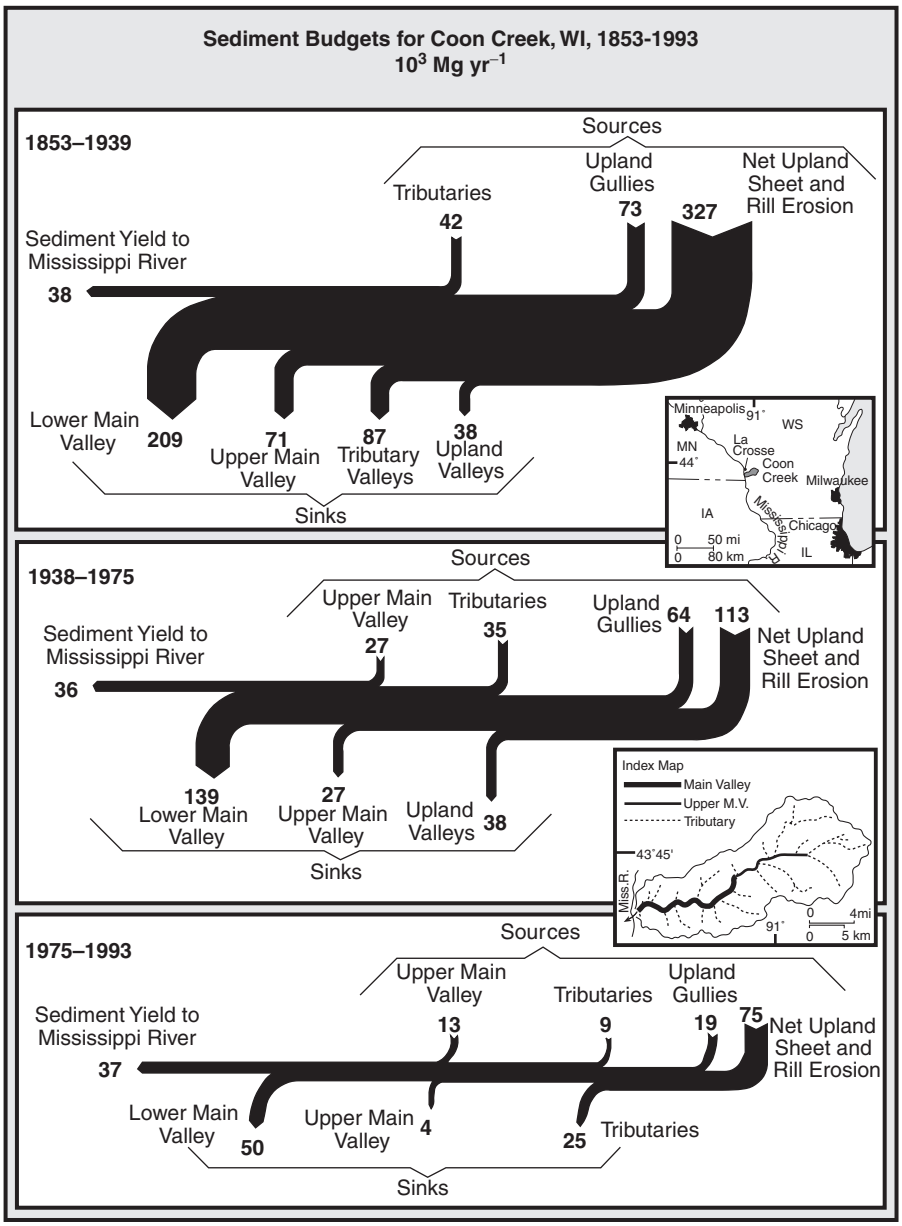

FIGURE 9.14 Sediment budgets for Coon Creek, Wisconsin, 1853 to 1993. This basin is about 25 km southeast of La Crosse, WI, and has an area of 360 km^2. Numbers are annual averages for the periods in 10^3 Mg/year (1 Mg = 1 metric ton). All values are direct measurements except net upland sheet-and-rill erosion, which is the sum of all sinks and the efflux minus the measured sources. The lower main valley and tributaries are sediment sinks, whereas the upper main valley is a sediment source. (From Trimble, S.W., *Science*, 285:1244–1246, 1999. The 1853–1939 and 1938–1975 portions of the figure are copyright AAAS, 1981; the 1975–1993 portion is copyright AAAS, 1999.)

already-existing problems (**Figure 9.16**C). Such stream processes as those described in Section 9.11.3, with impacts moving upstream or downstream, were termed by Schumm (1977) as a *complex response*. Note that the tributary channels, by virtue of 2 to 7 m of aggradation, had steepened their longitudinal profiles, thus increasing the potential erosional energy when the sediment supply was curtailed by improved land use. Schumm pointed out that aggrading streams could, in some cases, steepen their profiles to the point at which they became intrinsically unstable and might start degrading on their own without the mechanism of curtailed sediment supply as discussed here.

Stream and valley cross sections, or profiles, show these processes more clearly. **Figure 9.17** shows an upstream site where a 4m-high milldam was built across the stream in 1865, at which time the stream was flowing on bedrock. The local area was cleared for crops, and by 1930, the stream had aggraded about 5 m and buried the

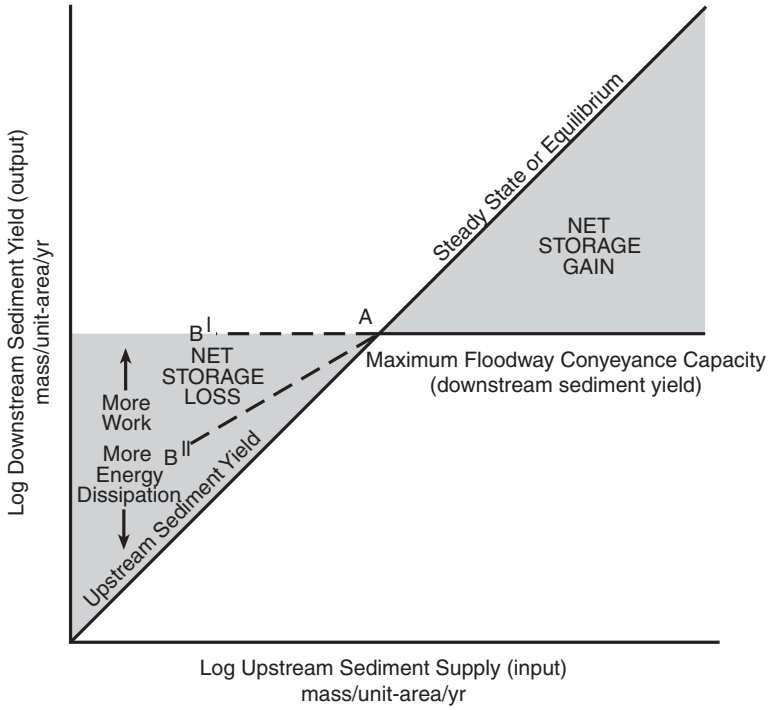

FIGURE 9.15 Schematic relation of downstream sediment yield and upstream sediment supply. Value A is the stream valley conveyance capacity. When upstream sediment supply exceeds A, the excess goes into storage, largely as vertical accretion on floodplains or channel filling. When upstream sediment supply drops below A, the stream attempts to use its excess energy to obtain sediment load from bed and banks. If sediment is easily obtainable and can be mobilized, it will be taken from storage, with the perfect case line AB′, with 100% of the available energy used for geomorphic work. Generally, much of the available energy will be dissipated, so line AB″ is more likely. (Modified from Trimble, S.W., *Am. J. Sci*., 283:454–474, 1983.)

dam more than a meter. With the improvement of land use, the stream had degraded about 2.5 m by 1969, exhuming the buried milldam. Local bridges were undermined by this degradation, demonstrating one cost of stream instability. During the same period, about 20 km downstream the stream aggraded almost 3 m, in large part from the migrating sediment brought from upstream storage (**Figure 9.18**). By 1969, the stream had aggraded almost to the bridge sills, built in 1934. This demonstrates another way in which unstable streams can be costly. This bridge flooded out frequently and had to be rebuilt and raised in the 1970s so there would be adequate flood clearance through the bridge opening. Despite these large masses of sediment in movement, only about 4% of all material estimated to have been eroded from Piedmont slopes during historic time has been transported to the edge of the region, the fall line (Trimble, 1975a).

9.11.5 Hydraulic Mining in California

While the above processes were caused by agricultural soil erosion, construction or mining can cause similar effects. In the mid-19th century in the Sierras of California, waste gravels from hydraulic mining were dumped into Sierra tributaries of the Sacramento River, burying the floodplains to 25 m in some locations (Gilbert, 1917; Adler, 1980; James, 1989). Finer particles were transported downstream, where they buried the floodplains of streams like the Yuba, Bear, and American Rivers and filled the channel of the Sacramento River, causing flooding at Sacramento and other cities. A court order to cease mining cut off the supply of new sediment in the late 1800s. Since then, hungry water has caused upstream degradation of more than 10 m in some locations. This has caused a "wave" of sediment to move through some downstream reaches, first aggrading, then degrading (**Figure 9.19**).

Lest it be construed that all accelerated erosion and legacies of sediment problems are human induced, note that some pressing sediment budget problems have their origins in the Holocene from effects of tectonism, glaciation, and volcanism (Church and Slaymaker, 1989; Slaymaker, 1993). In addition, past climatic changes have altered sediment budgets (e.g., Knox, 1999) and certainly will do so in the future. As you might guess, the instability under consideration has long been a topic in hydrologic studies. In particular, many basic principles have come from the classic work of Gilbert (1917), Happ et al. (1940), Mackin (1948), and E.W. Lane (1955b). Perhaps not perfectly, but we see encapsulated in the results presented here

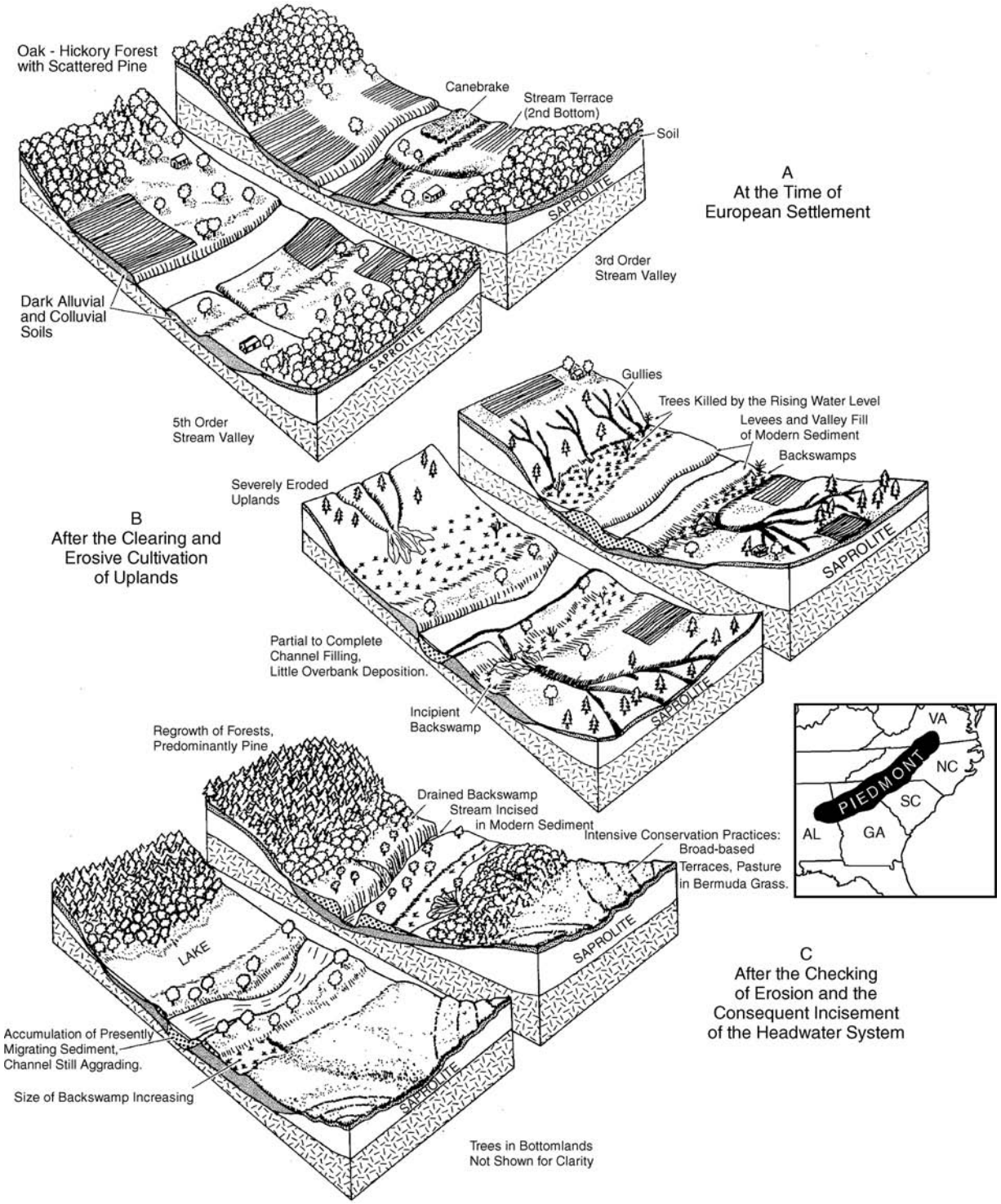

FIGURE 9.16 Block diagrams showing historic evolution of the southern Piedmont riverine landscape, 1700 to 1970, with the downstream migration of historic sediment and concomitant morphologic–environmental changes. The stream in the upstream block might drain 10 to 20 mi^2, while the downstream block might portray 50 to 100 mi^2. (From Trimble, S.W., *Man-Induced Soil Erosion on the Southern Piedmont, 1700–1970*, Soil Conservation Society of America, Ankeny, IA, 1974. Copyright S.W. Trimble, 1971.)

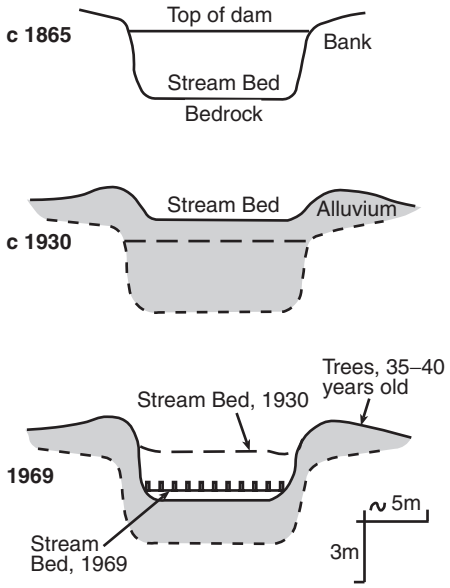

FIGURE 9.17 Processes in the upstream block of **Figure 9.16**, Periods 1 to 3. Aggradation and degradation at Mauldin Millsite, Mulberrry River, Hall County, Georgia. (From Trimble, S.W., *Culturally Accelerated Sedimentation on the Middle Georgia Piedmont*, U.S. Department of Agriculture Soil Conservation Service, Fort Worth, TX, 1970.)

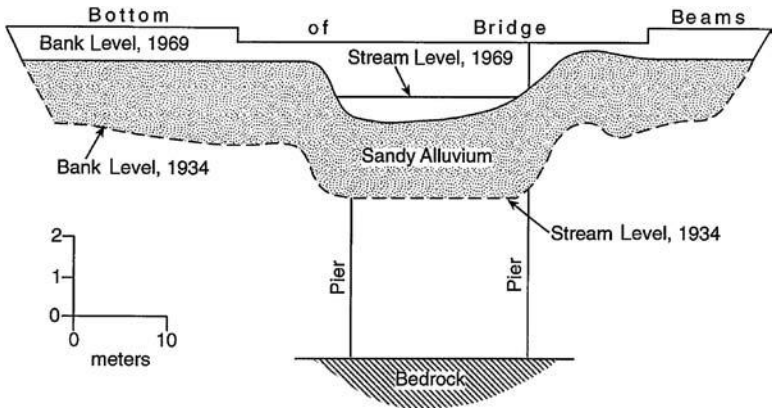

FIGURE 9.18 Processes in the downstream block, **Figure 9.16**, Period 3. Aggradation from migrating sediment at State Highway 53 bridge, Jackson County, Georgia. (From Trimble, S.W., *Culturally Accelerated Sedimentation on the Middle Georgia Piedmont*, U.S. Department of Agriculture Soil Conservation Service, Fort Worth, TX, 1970.)

many of the basic principles they described. For example, one of the most instructive diagrams published came from the work of Lane (**Figure 9.20**). He clearly showed how stream discharge and slope are balanced against sediment load and size (see Chapter 6, Equation 6.1).

9.11.6 The Driftless Area of the Upper Midwest

While the sediment budget examples given above are instructive, they depended on after-the-fact historical and archeological reconstructions to a great degree, so that one could not be very precise about some important processes and factors. A far better opportunity to study complex stream processes as related to land use concerns the Driftless Area (the Mississippi River hill country or Paleozoic plateau). There, important baseline work had been done in the 1930s that allowed relatively precise measures of stream and landscape changes that could then relate cause and effect in a meaningful way. The most intensely studied stream was Coon Creek, Wisconsin, a basin of about 360 km^2 (**Figure 9.21**). Aerial photographs were taken in early 1934 (e.g., **Figure 9.13A**), land use was catalogued, and water and sediment discharge measurements were made for a period of 6 years. Most important, however, were the 120 carefully surveyed stream and valley cross sections (profiles, **Figure 9.21**).

In 1973, Trimble found the original data for Coon Creek in the National Archives, enlisted the assistance of

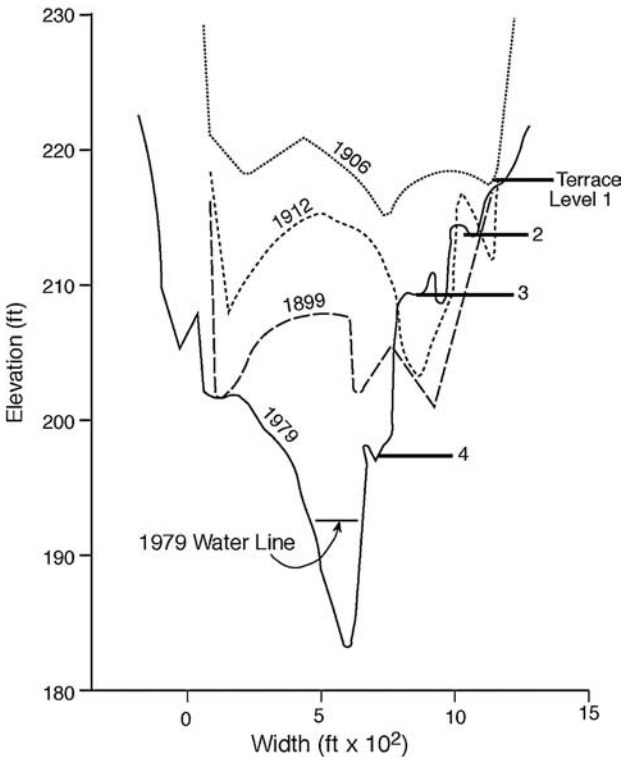

FIGURE 9.19 A "wave" of sediment moving through the Yuba River, California. Note the peak in 1909, from migrating sediment, reached about 3 to 4 decades after the cessation of hydraulic mining. (From Adler, L.L., Adjustment of the Yuba River, California to the Influx of Hydraulic Mining Debris, 1849–1979, master's thesis, University of California, Los Angeles, 1980.)

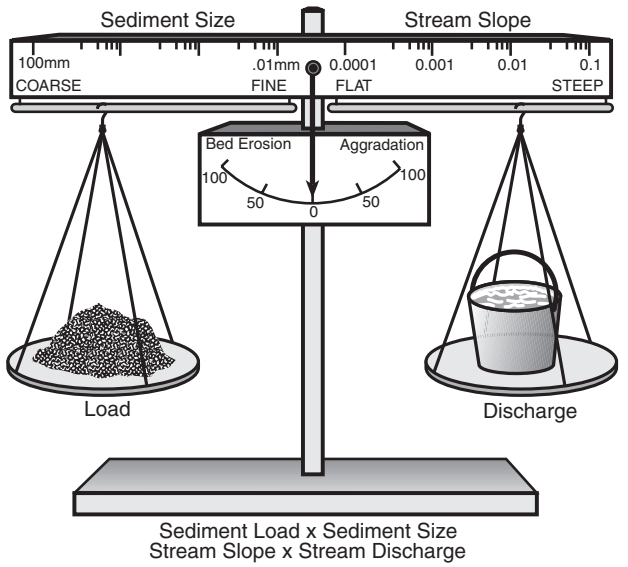

FIGURE 9.20 Another view of stream behavior as a function of discharge and slope on the one side and sediment load and size on the other. Compare with **Figure 9.24**. (From Lane, E.W., 1955a. Redrawn with permission from Phillip Williams & Associates, Ltd.)

the project's designer, Stafford C. Happ, and over the following 5 years, resurveyed the old profiles, collected data on more than 100 new profiles and many archeological excavations, and performed corollary work in other regional streams. Work has continued, and resurveys were performed in 1991 to 1995 (Trimble, 1999). Coon Creek may be the most comprehensively studied stream basin in the world (Glanz, 1999). The following is a thumbnail sketch of what has been published so far.

As shown earlier, the areas were settled by Europeans starting in 1853. The people who eventually came to farm were largely Germans and Scandinavians, who were, in fact, good farmers by standards of that time. However, their European experience did not prepare them for the heavy and intense rainfall that fell in this region (Koeppen Dfb). The excellent soils, much of them mollisols formed on loess, were so deep and fertile that they were thought to be "inexhaustible"; indeed, several decades of farming seemed to change matters little. That is, there was a "lag" of decades before poor land use manifested itself hydrologically because of deterioration of soil condition.

By the early 20th century, soils had been in use 50 to 60 years, and undoubtedly, organic material and structure had insidiously deteriorated, endopedofaunal activity was decreased, bulk density had increased, and infiltration capacity had decreased. While we have no data on the soils of that period, later studies have shown that active soil organic material decreases to a fraction of its original levels after 50 years of agriculture (D. Foster et al., 2003). What we do know is that overland flow, soil erosion, and flooding became noticeable by the turn of the 20th century and was out of control by the mid-1910s and 1920s. By this, we mean that floods were frequent and intense, and streams and floodplains were aggrading with sediment at a rate of 150 mm/year in some locations. Roads, bridges, farms, and even villages were literally buried in the region.

This situation continued until the mid-1930s, when modern soil conservation measures became available, and the federal government aggressively sponsored the installation of such measures. Only then was soil erosion and high runoff response brought under control. Even with the measures installed, it was two to three decades before flooding and soil erosion were brought to the present low levels. So, there was again a lag between the time that land use practices (this time, good ones) were implemented and the hydrologic effects were seen (**Figure 9.22**). Erosive land use, the independent variable, is the combined CP factors of the universal soil loss equation (discussed in this chapter) times 100 to give whole numbers. The dependent variable, hydrologic response–geomorphic work, is a combination of erosion and sedimentation rates. There is actually another lag between erosion from the slopes and deposition along streams, but **Figure 9.22** is simplified (see Trimble, 1990, for full data). There was little further hydrologic response to expanding agriculture

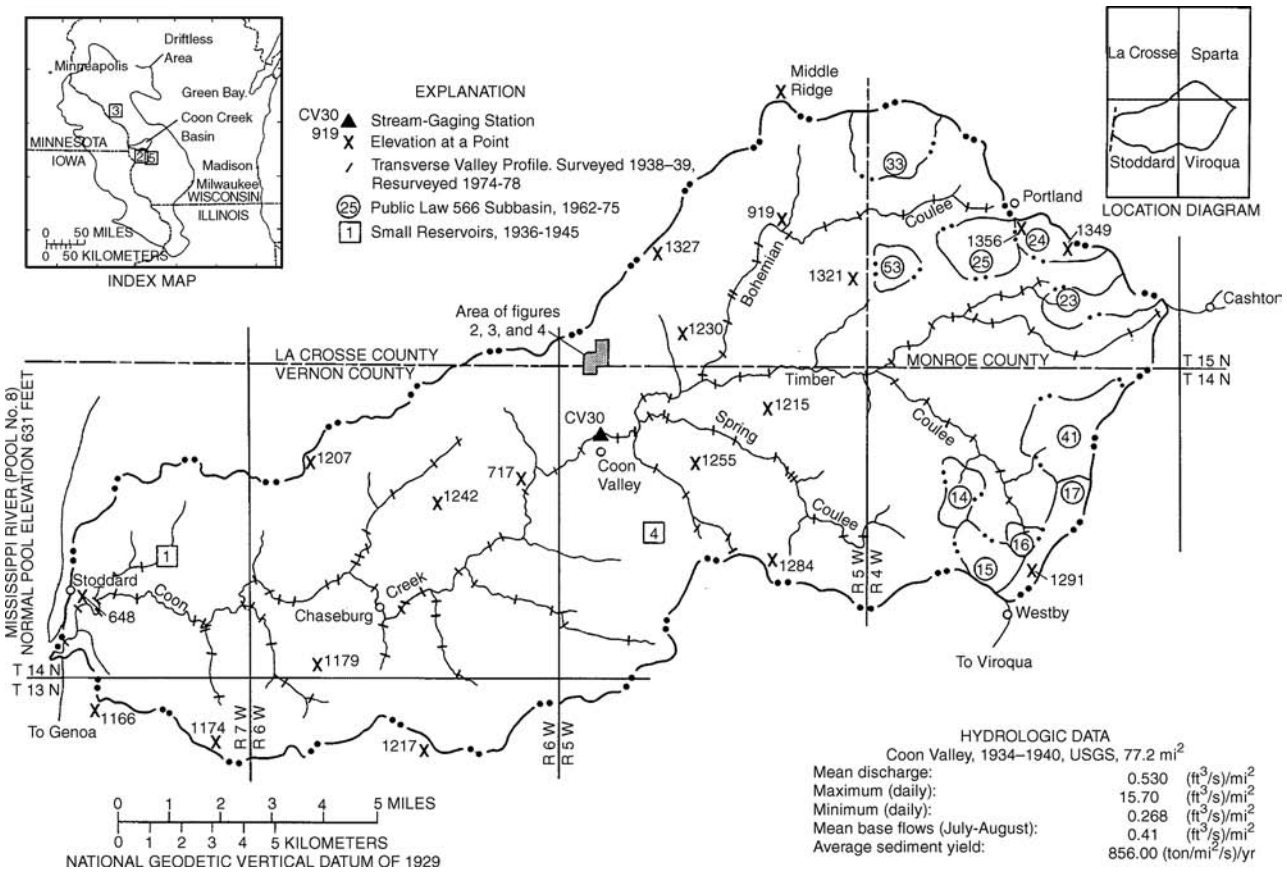

FIGURE 9.21 Coon Creek, Wisconsin, showing the 120 stream and valley cross sections (profiles) surveyed in the 1930s and again in the 1970s. Also shown are subbasins, debris basins, and other research locations in the study. (From Trimble, S.W., and S.W. Lund, Soil Conservation and the Reduction of Erosion and Sedimentation in the Coon Creek Basin, Wisconsin, USGS Professional Paper 1234, 1982.)

until shortly after 1900, when erosion was out of control. That is, the ubiquity of eroding rills and gullies was self-feeding and would not respond to even moderate land use changes. One might think of this as a "threshold" phenomenon. Once triggered, it would take heroic measures to bring it under control. Indeed, control of the landscape was only gained by the massive soil conservation measures and landscape restoration of the 1930s and 1940s. The effects of these measures were still being experienced in the 1960s and probably still are. Thus, the two lag functions together give a hysteresis loop, much like that discussed regarding soil moisture and what will be discussed between water and sediment discharge of a stream (the rising and falling limbs).

But, as seen before, decreasing erosion and creating hungry water created new problems in an already-unstable stream system. As discussed for the Piedmont, different stream orders or basin regions had different processes operating simultaneously. What happened in different parts of the basin is summed nicely by **Figure 9.23**, which shows historical sediment budgets for three zones of the basin, tributaries, upper main valley (UMV), and lower main valley. One might think of these processes as "distributed" in the same sense of any distributed models that attempt to show cause and effect and where and when something happened. In reality, these (**Figure 9.23**) are not three discreet zones, but the processes shown vary differentially and continuously down the valley. The three zones or regions are grouped for data analysis and for easier explanation.

Tributaries. Tributary channels were originally quite small, so narrow that "one might jump across" as the early settlers recounted (McKelvey, 1939). As sediment from slope erosion started moving downstream in appreciable quantities, tributaries initially accreted along their floodplains (**Figure 9.24**). As stream banks became higher, more and deeper flow was constrained to the channel, thus increasing stream power and causing the banks to erode (Happ et al., 1940).

By about 1935 (**Figure 9.24**), stream channels were rapidly eroding and widening by lateral erosion, leaving

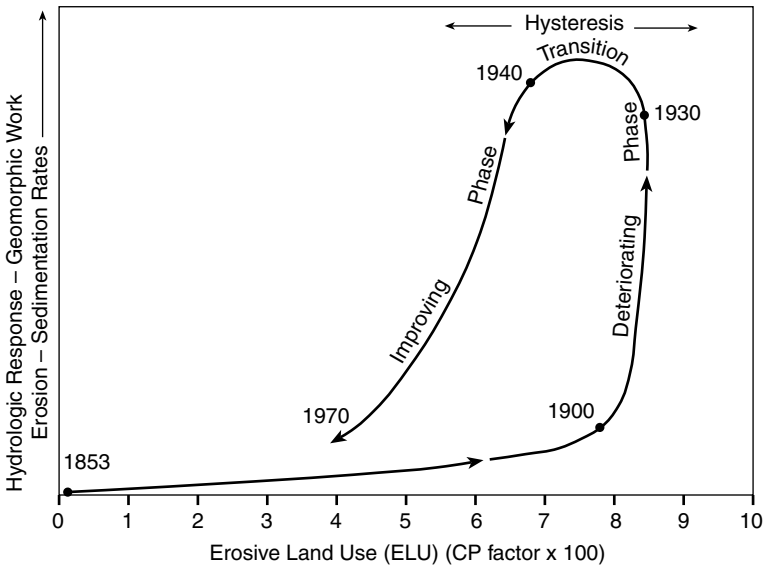

FIGURE 9.22 The relationship between intensity or erosiveness of land use and hydrologic response or geomorphic work, Coon Creek, Wisconsin. With the expansion of agriculture after 1853, there was little response until the early 20th century, when the landscape was out of control, bearing no relation to the input. Aggressive implementation of soil conservation measures in the 1930s brought the landscape back under control, but there was yet another lag in the response of the land. The result is this hysteresis function. There was yet another hysteretic relationship between erosion and sedimentation. This is not shown here, but can be seen in the cited study of Trimble and Lund (1982). (From Trimble, S.W., and S.W. Lund, Soil Conservation and the Reduction of Erosion and Sedimentation in the Coon Creek Basin, Wisconsin, USGS Professional Paper 1234, 1982.)

low, inset gravel and cobble bars on the inside of bends (**Figure 9.25**A). These wide, inset streamways containing the channel and bars were termed *meander plains* (Melton, 1936; Happ et al., 1940) By this time, hydrologic response was very high, so even small storms often brought vast amounts of stormflow. This excess energy continued to widen the meander plain. By 1950 (**Figure 9.24**), the effects of land use improvements were beginning to take hold, so the rate of bank cutting and meander plain development was declining. Also by this time, the high-water channel formed by the meander plain was so large that very few flows exceeded its discharge capacity; indeed, very few surveys showed any accretion on the old, historical floodplain between 1938 and 1974. This means that the old historical floodplain had become a fluvial terrace. By 1974 (**Figure 9.24**), a much milder hydrologic regime was permitting the deposition of fine sediment over the old, coarse bars, by then vegetated, creating what Trimble (1975b) hypothesized as new, lower floodplains diagnostic of the new and presumed milder hydrologic regime brought on by improved land use. This process was also investigated by Johnson (1976), Knox (1977), and Magilligan (1985), who found that it was also occurring in areas to the west and south.

Many might wonder if these significant changes of fluvial landscape might have been brought on by changes in climate. Refer to **Figure 2.7**, which shows that climate changes were completely out of phase (negatively correlated) with the changes seen here. In other words, the effectiveness of precipitation was at a minimum at just about the time that hydrologic disruption, erosion, and sedimentation were at their peak. Conversely, decreases of erosion and sedimentation occurred during a period of higher precipitation.

For some time, the hypothesis of a milder hydrologic regime brought on by improved land use (Trimble, 1975b, 1976) remained just a hypothesis, although it was supported by morphologic evidence, like the new floodplains, and by field observations. While base flow of Coon Creek was much higher in the 1970s than in the 1930s, the time was too short to be statistically significant, and the role of precipitation trends was uncertain. However, longer term regional streamflow data were used in the last decade to show that, in fact, stormflow has abated, while base flow increased (Potter, 1991; Gebert and Krug, 1996; Krug, 1996; Knox, 1999; Kent, 1999). This milder hydrologic regime is reflected in many ways (**Figure 9.25**B). Tributary channels have continued to become narrower over the past 30 years, and the water quality has continued to improve. Even watercress and other aquatic vegetation have reappeared in streams where there was only gravel 50 years earlier. Perhaps the most convincing evidence of a milder hydrologic regime, higher base flow, and better water quality is the improvement in fish habitat. At the

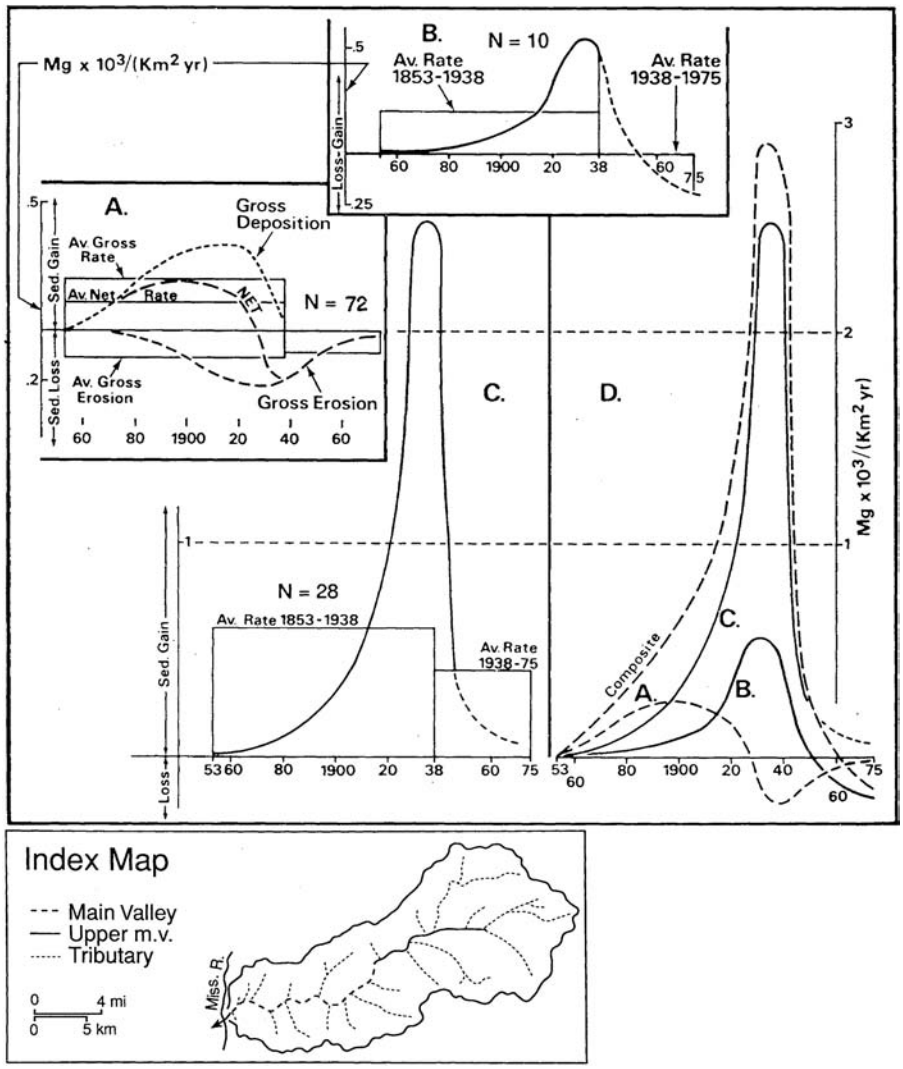

FIGURE 9.23 The distributed sediment budget model for Coon Creek, Wisconsin, 1853 to 1975, showing how processes and sediment moved downstream. (From Trimble, S.W., *Am. J. Sci*., 283:454–474, 1983. Copyright 1983, *American Journal of Science*, Kline Geology Laboratory, Yale University. With permission.)

time of settlement, these tributaries were home to brook trout *Salvelinus fontinalis*, a species known for acute intolerance to turbid water and flooding. By the 1930s, only exotic brown trout *Salmo trutta*, which had to be stocked, were able to survive the higher sediment concentrations, warmer water temperatures, and stream channel instability of that period. With the habitat improvements of the past few decades, the brook trout now not only survive in these once-desolate tributaries, but also reproduce (Thorn et al., 1997; Trimble and Crosson, 2000).

Apart from the incredible recovery of these tributaries, there are some instructive applications of stream power principles (**Figure 9.26**, refer to **Figure 9.24**; for a similar treatment, see Knox and Hudson, 1995). In the presettlement stage, flow spread out thinly over the floodplain, so that unit stream power was low. With the aggradation of the floodplain and commensurate raising of the stream banks (Stage 2), streamflow was more constrained to the channel, where it would have flowed faster and deeper and would have developed much more stream power, thus eroding the channel. As the meander plain widened (Stage 3), similar flows would have been spread out more, thus becoming shallower or less rapid, and would have developed less unit stream power. As meander belts continued to widen (Stage 4), flows became shallower and even less rapid, so for a given discharge, stream power has continued to decrease, probably since about 1900 or so. However, we know that hydrologic response was increasing at the same time the morphology was yielding less stream power for a given discharge. Thus, early tributary erosion has more of a morphologic explanation, while later channel erosion has more of a hydrologic

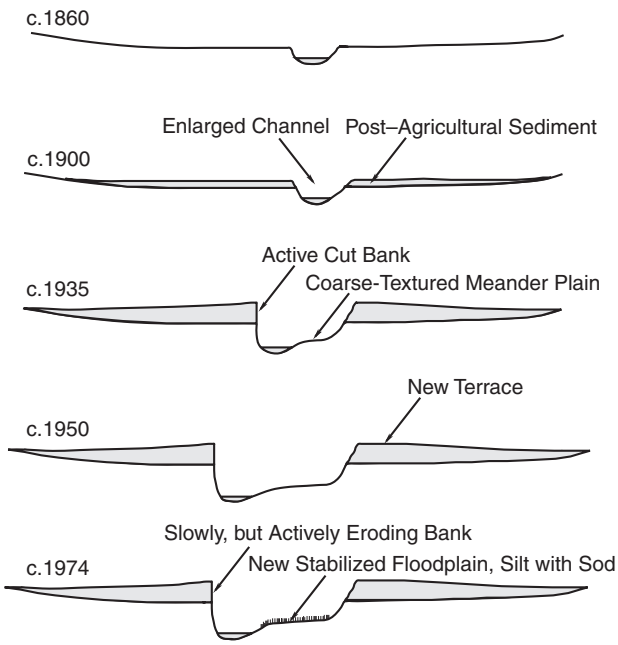

FIGURE 9.24 Schematic model of changes of historic stream and valley morphology for Coon Creek and other Driftless Area tributaries, 1860 to 1974. (From page 16 of a set of mimeographed handouts by S.W. Trimble for field trip to Driftless Area, April 1975, sponsored by the Association of American Geographers and led by George Dury, James C. Knox, W.C. Johnson, and S.W. Trimble.)

regime explanation. Of course, all of this ignores other variables, such as sediment concentrations, sediment size, and the effect of cattle on the resistance of stream channels to erosive force from high flows (Trimble and Mendel, 1995).

Tributaries have had a complex role in the basin sediment budget (**Figure 9.24**). At first, they were a sink; then, despite complex processes of riparian accretion and erosion, they were net sources of sediment to downstream areas. Net stream channel erosion is always serious for downstream sedimentation because sediment is released directly into the stream so it can be more efficiently conveyed downstream. Since the surveys of the 1970s, the new tributary floodplains have become a serious sediment sink, with 150 mm of accretion since then common. Interestingly, the old, historic floodplains have received little sediment. This is because those surfaces are now stream terraces (i.e., relict floodplains) and now are rarely inundated by floods.

A major difference can be noted between the tributary processes in the Driftless Area and those seen on the Piedmont and in the Sierras, where aggradation of the channel by coarse material took place. After the period of the big sediment influx, initial channel readjustment on the Piedmont and in the Sierras was vertical incision or degradation, while in the Driftless Area, it was lateral or bank erosion. In **Figure 9.24**, note that the Driftless Area tributaries are underlain by gravel, which made them much more resistant to erosion than the silty banks. Since the channels were rarely filled or aggraded with material, there was rarely an oversteepened profile to be readjusted as seen for the Piedmont.

The Upper Main Valley (UMV). The UMV (**Figure 9.23**) has had a history similar to that of the tributaries, but since the processes were moving downstream, the same processes occurred later. The other major difference is that historical sediment storage was much greater in the UMV. Whereas it was rare to see historical sediment more than 1 meter thick in the tributaries, 2 to 3 meters was the norm in the UMV, with banks often 4 m high. Most of this reach was like a flume at the time of the surveys in the late 1930s. Thus, when bank erosion started there in the 1940s, it was a major problem because this erosion sent so much sediment downstream. Trimble (1976, 1983, 1993) recognized it as such and monitored this reach very closely by surveying many new profiles (**Figure 9.27**). This reach looked much like a flume in the 1930s, but by the 1970s, had developed a meander belt much like those already seen in the tributaries. A plan example of this type of reach is that of the Whitewater River in Minnesota near Elba (**Figure 9.28**). Again, note that the channel was narrow like a flume in 1940, but by 1990, had created a wide meander plain about 2.5 m below the historical floodplain. Sediment storage loss from this 275-m long reach was 21,450 tonnes over a 50-year period or an average of about 430 tonnes per year. Since this reach is representative of several kilometers of stream, the potential for downstream sedimentation and sediment yield becomes clearer.

From a management standpoint, the question was what to do about these prolific sources of sediment. Some managers wanted to cut the banks down and riprap the toe, but doing that over a long reach would be extremely expensive and might destabilize the downstream reaches by cutting off the supply of sediment and creating hungry water (Trimble, 1993). However, a model of the processes suggests that the matter will take care of itself over time (**Figure 9.29**). We enter the model after Stage 1, when the stream is beginning to create the meander plain. At that time, the stream is close to long reaches of the high cut banks on both sides, so that almost any lateral movement will cut into a high bank and release a net flow of sediment. Thus, there are huge sediment losses as the meander belt evolves through Stages 2 and 3, but by then, there is an increasing area of low floodplain so that when the stream erodes part of that away, it is replaced on the other side by a bank just as high, and there is no net loss. Moreover, the increasing area of new floodplain, because it is vegetated, is a sediment sink for vertical accretion (**Figure 9.24**). By Stage 4, the reach is a major sink for sediment. Again, we are seeing a morphologic feedback by which stream power

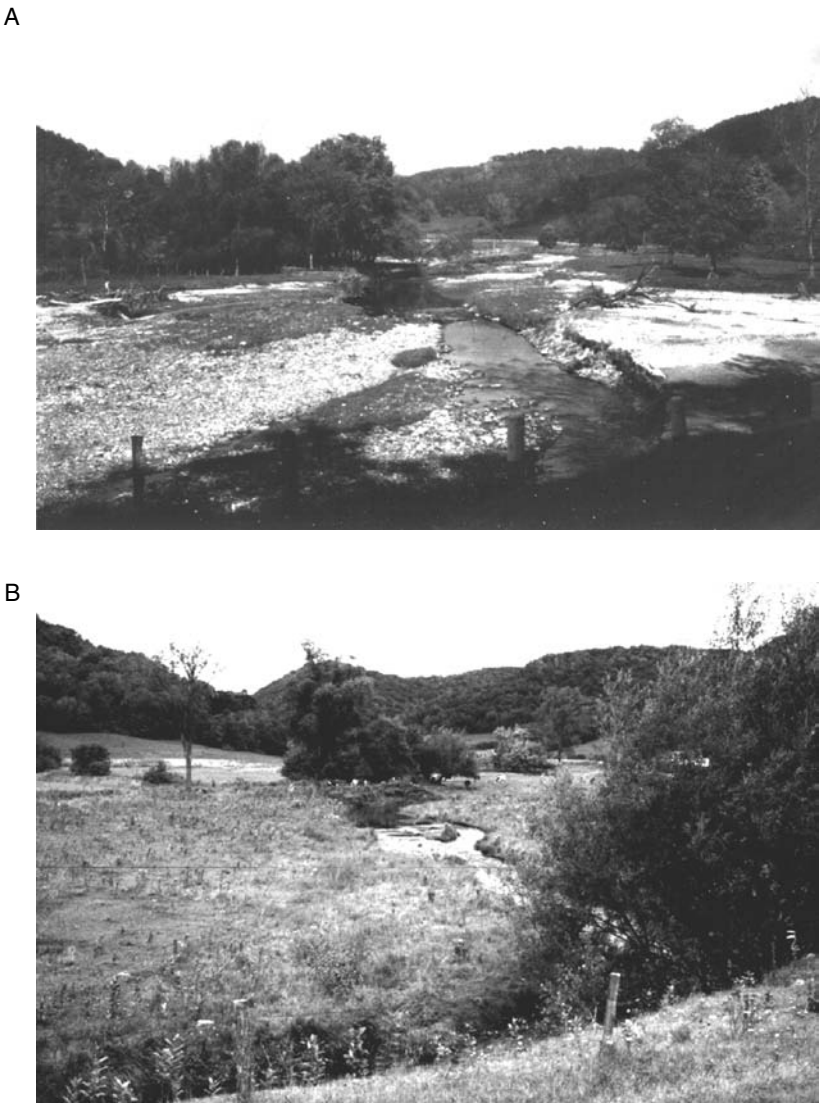

FIGURE 9.25 Change of tributary conditions in Driftless Area, 1940 to 1974. (A) Photo of Bohemian Coulee (SE1/4, SE1/4, Sec. 33, T15N, R5W, La Crosse County, Wisconsin). This photo was made by Stafford C. Happ in 1940 to show a "typical tributary" of that time. Refer to 1935 in **Figure 9.24**. Note the highly unstable quality, with coarse sediment, cut banks, and wide stream. (B) Photo at the same site by S.W. Trimble, June 1974. The stream has become even more stable and narrow since 1974. (From Trimble, S.W., and P. Crosson, *Science*, 289:248–250, 2000.)

is reduced as the meander belt widens. The high banks, mostly at some distance from the stream, are no longer as vulnerable. Trimble had earlier predicted that the UMV reaches, a major sediment source from 1940 to 1990, might be a sediment source for decades, but the 1990s surveys proved that incorrect: Gains and losses for the period from 1975 to 1993 were beginning to balance, and the trend appears to be toward sediment accumulation (Trimble, 1999).

Lower Main Valley. Finally, the lower main valley (**Figure 9.23**) has been a sediment sink from the time of settlement. What is remarkable about this reach, however, is that the sedimentation rates reached such heights in the 1920s and 1930s, with 150 mm of vertical accretion per year about the norm in that period. Such rates of vertical accretion were so overwhelming that roads, bridges, villages (e.g., Beaver, MN, and Chaseburg, WS) were buried during this period. While the accretion rates have been dramatically reduced, the reach continues to aggrade, with much of the material coming from upstream channel erosion (**Figure 9.30**). However, channel erosion from upstream may be having as much qualitative effect as quantitative effect. Since material eroded from a channel and banks is

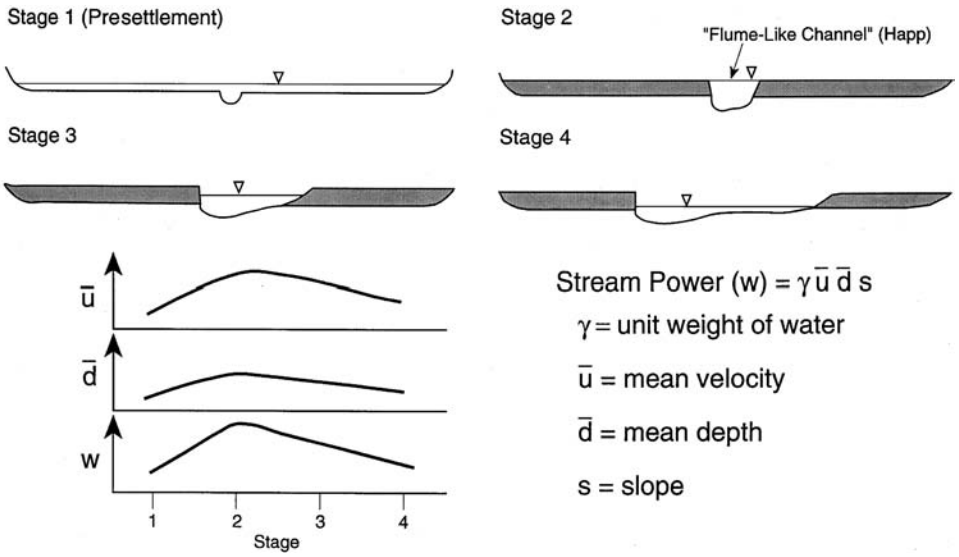

FIGURE 9.26 Stream power and the transformation of stream and valley morphology, Driftless Area tributaries. With the small stream channel of Stage 1, floods spread out over the floodplain, keeping depth, velocity, and stream power low. With accretion of the floodplain and stream banks with historic sediment in Stage 2 (circa 1900), greater flows were restricted to the channel, thus increasing depth, velocity, and stream power so that the channel erosion shown in 1900 in **Figure 9.24** must have been very rapid. In Stages 3 and 4, the channel erodes laterally, so that flows are spread, with decreases of depth, velocity, and stream power. By the latter stage, fine sediment has covered the old gravel bars, and new floodplains are formed as shown in **Figure 9.24**. (From presentation to the Association of American Geographers annual meeting, San Diego, CA, April 20, 1992. Ron Shreve made important suggestions in the preparation of this diagram in 1991.)

reworked, the coarser portion of the sediment is left in the stream, while the finer material is transported downstream or is deposited on the distal floodplain. The coarser material now in the channel, mainly fine sand, has two major impacts. First, it aggrades the channel and the natural levees to either side, but is not transported into the distal floodplain (**Figure 9.30**). Thus, the now superelevated channel and levees raise the local groundwater level, in part because water behind the levees cannot get to the stream. Backswamps become more pronounced, becoming swamps or even lakes in some distal locations. The second problem is that this migrating coarse sediment can have grave downstream consequences. As an example, such migrating sand from tributaries has raised the bed of the Trempeleau River more than a meter at Arcadia, WS, thus raising local groundwater and flooding basements in Arcadia. While the quantitative effect of eroding upstream channels might be declining, the qualitative effects just described may last for decades or more.

9.11.7 Urban Streams

Urban streams provide us with a different sediment budget — one of general channel erosion and sediment movement downstream. During urban construction, however, there is much local slope erosion, and channels may actually aggrade at first (Wolman, 1967). Elsewhere in this text, we looked at how the "waterproofing" of built-up urban areas affects streamflow. All flows for any given precipitation event are increased, but it is the smaller events (1- to 10-year return interval) that are magnified the most. The effect of these greater stormflows is to increase stream power and thus erode and destabilize streams. Note that not only are the flows greater, but with urban land use, they initially have less sediment and therefore have even more erosive power. The net result is that channel size may expand several times in a few years. A good case in point is the San Diego Creek in rapidly urbanizing Orange County, California, where rapidly eroding earthen channels alone are responsible for most of the sediment filling Newport Bay (**Figure 9.31** to **Figure 9.33**). Such rapidly eroding channels are problematic not only from the sediment they produce, but also from the fact that they destabilize expensive urban land and are unsightly. Highly scoured channels such as these often have low places where water collects and stagnates during low-flow periods and produce aesthetic and health problems.

This brief sketch of sediment budgets is only an introduction. For further reading, see the work of Schumm (1977), Graf (1988), Cooke and Doornkamp (1990), Swanson et al. (1982), Meade (1982), Abrahams and Marston (1993), I. Foster et al. (1995), Gurnell and Petts (1995), Trimble (1995), Reid and Dunne (1996), Anderson et al. (1996), Knighton (1998), A.G. Brown and Quine (1999), and Darby and Simon (1999).

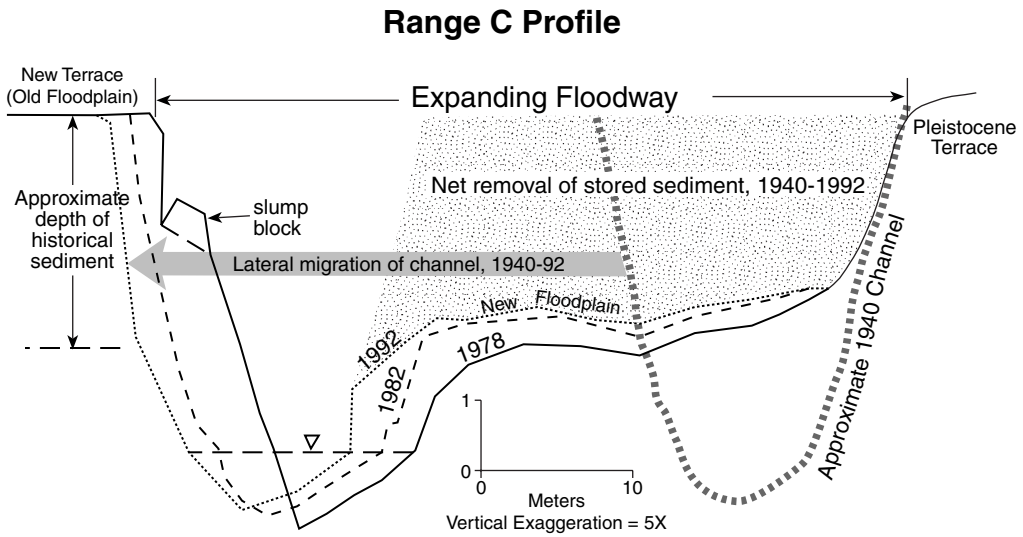

FIGURE 9.27 Channel transformation in upper main valley, Coon Creek, Wisconsin. The channel was "flumelike" in about 1940 and flowed by the Pleistocene terrace at that time (approximate 1940 profile shown in ghost outline). Note that the historical floodplain, adjusted to the effective discharge of that time, had aggraded almost to the level of the Pleistocene terrace; indeed, many such terraces were buried. Since 1940, the channel has migrated (leftward) to its present location. As it continues to migrate, the new floodplain is built up to the height of present-day effective discharge. Note that this "meander belt" expansion has left the old floodplain as a relict floodplain or terrace. Net removal of stored alluvium is about 100 m^2 and is shown in shadow. This loss since 1940 would be about 100,000 m^2/km or about 130,000 Mg/km at a bulk specific gravity of 1.3. However, note that, in recent years, the gain of vertical accretion on the new floodplain is almost as much as that lost from the high cut bank. (From Trimble, S.W., *Science*, 285:1244–1246, 1999.)

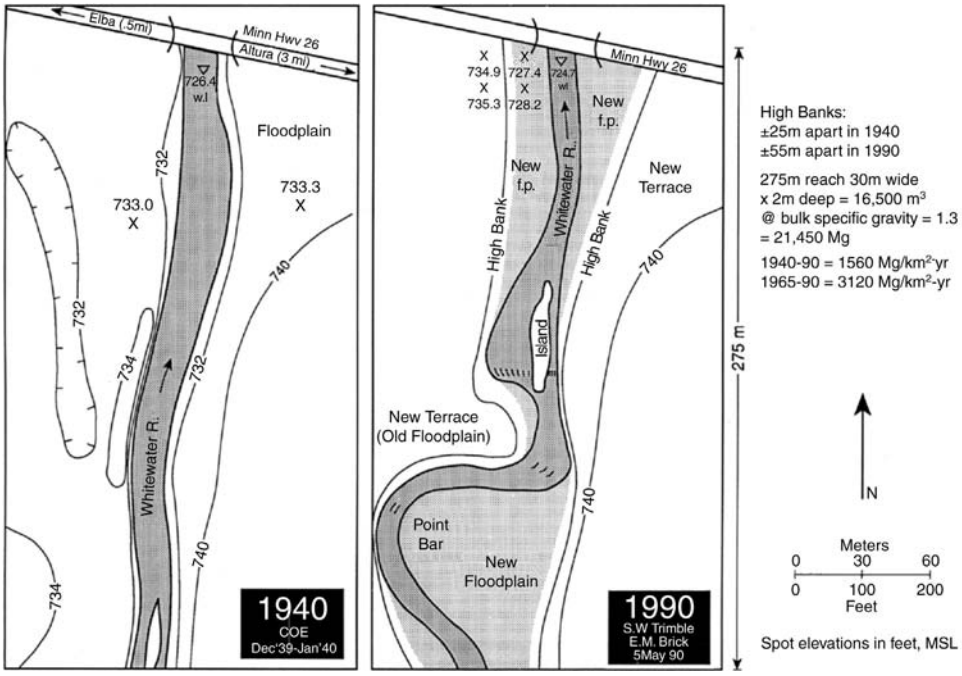

FIGURE 9.28 The same upper main valley channel processes as seen in **Figure 9.24** in plan view, Whitewater River at Elba, MN. The rate of sediment storage loss here (21,450 Mg/275 m per 50 years) would be about 78,000 Mg/km per 50 years, a rate on the order of that shown in **Figure 9.23**. (From Trimble, S.W., *Phys. Geogr.*, 14:285–303, 1993. With permission of Bellweather Publishing.)

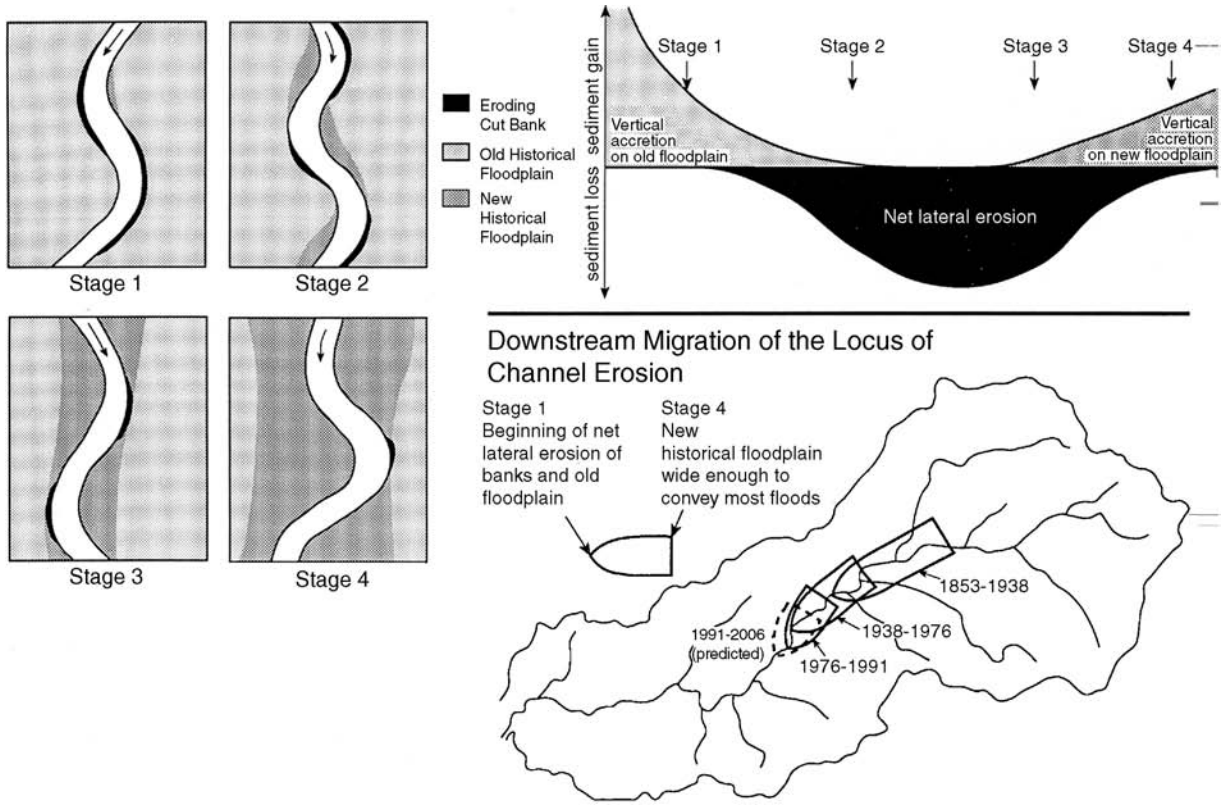

FIGURE 9.29 A model of the changes of sediment budget accompanying the changes of morphology seen in **Figures 9.24** and **9.25**. Note the dual morphologic feedback: (A) as the stream moves from Stage 3 to Stage 4, it no longer has the frequent contact with the high banks, and (B) the wider floodplain provides more opportunity for sediment storage. Thus, the zone eventually becomes a sediment sink. (Modified from Trimble, S.W., *Phys. Geogr.*, 14:285–303, 1993. With permission of Bellweather Publishing.)

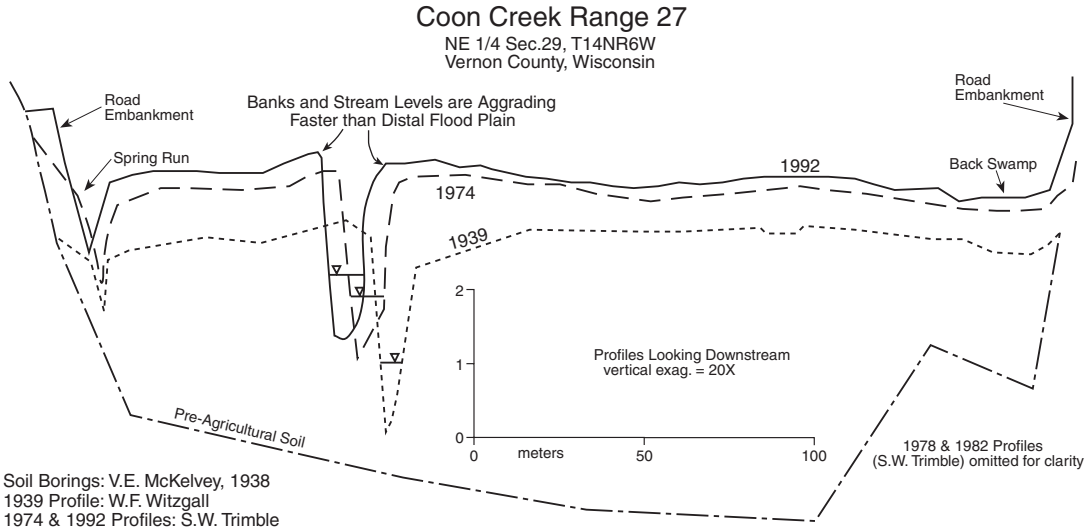

FIGURE 9.30 A typical profile in the lower main valley of Coon Creek, Wisconsin, the zone of continual accretion. While the rate of aggradation decreased greatly after 1939, the aggradation was greater near the stream than at distal areas on the floodplain. The result is that the natural levees keep the water level higher in the backswamps. This differential aggradation is thought to be from coarser sediments eroded from upstream bed and banks. (From Trimble, S.W., *Phys. Geogr.*, 14:285–303, 1993. With permission of Bellweather Publishing.)

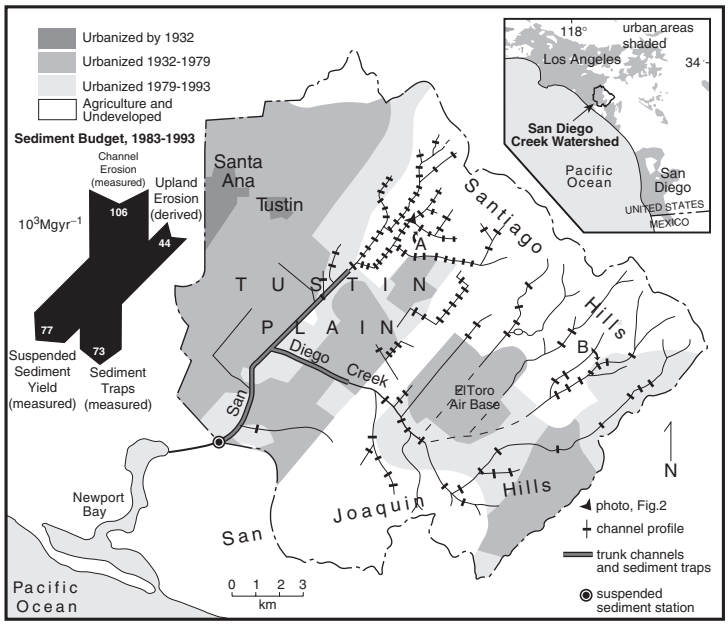

FIGURE 9.31 San Diego Creek, California, showing the earthen stream channel network and the expansion of urban land, 1932 to 1993. Paved channels and channels lying upstream from reservoirs were not included in this study. The cross-sectional channel profiles shown are those remaining in 1993. Sediment yield is that measured at the station plus accretion in the trunk channels and sediment traps. Inset is the sediment budget. A and B indicate the profiles shown in **Figure 9.32** and **Figure 9.33**. (From Trimble, 1997a. Copyright AAAS, 1997.)

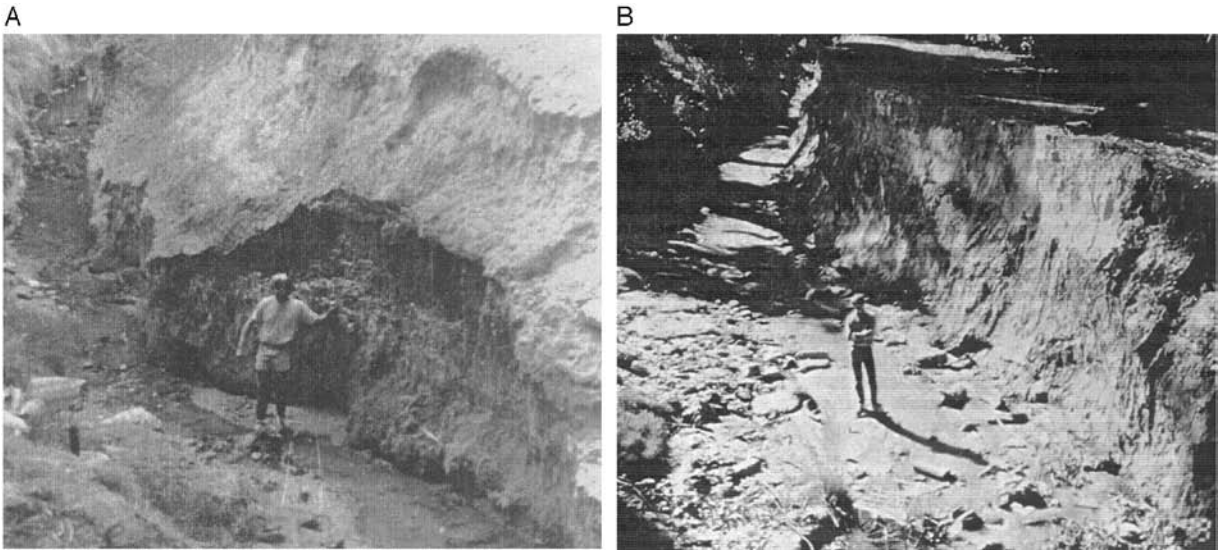

FIGURE 9.32 Photos showing urban channel erosion in Hicks Canyon Wash, San Diego Creek, California: (A) 1979 (B) 1993. A person stands at approximately the same location in both photographs. Note the retreat of the cut bank to the right. Arrows mark the location of surveyed profiles in 1983 and 1993 (see **Figure 9.33**). (From Trimble, 1997a.)

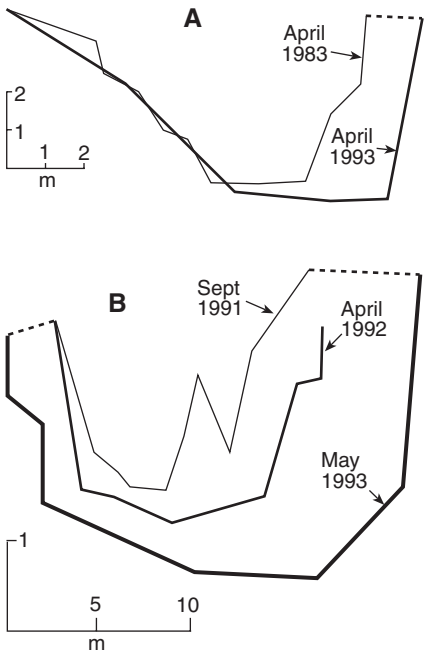

FIGURE 9.33 A. Surveyed stream channel profiles, Hicks Canyon Wash, San Diego Creek, California, 1983 and 1993 (see **Figure 9.31** and **Figure 9.32**). The rate of erosion at this profile was 0.47 m^3/year per meter of channel. At a bulk specific gravity of 1.44, this would be 0.7 Mg/m per year, slightly less than the average for this type of channel. B. Extreme erosion of Borrego Canyon Wash Profile 3, directly downstream from an urbanizing area during the wet years of 1992 and 1993. The rate of erosion was about 20 m^3 or about 29 Mg/year per meter of channel. This reach has since been stabilized. (Trimble, 1997a. Copyright AAAS.)

PROBLEMS

9.1. (a) For the following cities, determine the average annual rainfall (**Figure 2.6**) and the *R* factor (**Figure 9.3**): New Orleans, LA; Kansas City, MO; Minneapolis, MN; Denver, CO; and Atlanta, GA. (b) Plot *R* vs. annual rainfall. (c) From your graph, estimate the *R* factor for Brasilia, Brazil, which has an annual rainfall of 60 in. (d) According to Bertoni and Lombardi (1993), the *R* factor for Brasilia is about 440. Comment on the reliability of this method for estimating *R* in Problem 9.1c.

9.2. Determine the soil erodibility factor *K* for a soil that has the following properties: 60% silt plus very fine sand; 0% coarse sand; 3% organic matter; very fine granular soil structure; and slow permeability.

9.3. If the predicted soil erosion for a given set of conditions is 10 tons/acre for a 450-ft slope length and three terraces are installed, what is the predicted soil erosion rate from the slope for a 150-ft slope length if all other conditions remain unchanged and the slope is 8%?

9.4. Determine the annual soil loss from an urban area that is under development and has the following characteristics: average annual rainfall erosivity of 200; 500-ft slope length and 4% steepness; no vegetation; and 0.4 soil erodibility factor.

9.5. (a) Determine the soil loss for a field at your present location if $K = 0.30$, slope length is 300 ft, slope steepness is 10%, $C = 0.2$, and up- and downslope farming is practiced. (b) What conservation practice should be adopted if the soil loss is to be reduced to 4 tons/acre?

9.6. You work for the Tennessee Department of Natural Resources and are in charge of evaluating applications for permits for surface mining. A mine operator wishes to mine a steeply sloping forested watershed located in the Appalachian Mountains (eastern Tennessee). The watershed currently exhibits the following characteristics: soils with an 0.4 erodibility factor; about 10% slope steepness and about 2000-ft long; vegetation is an unmanaged forest with a medium stocked stand (50% tree canopy area and about 80% forest litter cover). (a) Determine the average annual erosion rates prior to mining. (b) Following mining, the operator will place terraces every 1000 feet; replace the land at average slopes of 8%; and reclaim the area by planting grass. It is anticipated that there will be no appreciable canopy and a 40% ground cover. If the maximum allowable soil loss is 4 tons/acre, would you give the mine operator a permit? State your reasons.

9.7. (a) Determine the annual soil loss from a 200-acre farm in central Indiana. The farm has Blount soils, and typical slopes are 1000 ft long with 2% steepness. The farmer uses conventional tillage in the autumn and has a corn–soybean rotation. (b) What percentage change in the annual soil loss would you expect if the farmer switched to a no-till farming system?

9.8. Determine the sediment yield during a 10-year period from the 200-acre farm in Problem 9.7. The farm is located on a 5-mi^2 watershed.

9.9. From the principles presented in this chapter, discuss three management techniques to minimize soil erosion on the slopes of a popular ski resort.

9.10. A watershed in western Ohio was intensively farmed for almost 100 years and experienced severe erosion. The farmers all abandoned their farms, and the predominant vegetation on the watershed reverted to native woodland. When

the woodland was about 80 years old, a large recreation and flood control reservoir was constructed on the stream draining the watershed. The engineers were surprised to discover sedimentation rates from the watershed were similar to cropland rates. (a) What do you think was the source of the sediment? (b) Describe a method to reduce sedimentation in the lake.

9.11. A reservoir is constructed on a stream draining 5 mi^2 (1 mi^2 = 640 acres). Two thirds of the watershed has an estimated upland erosion rate of 4.5 tons/acre/year, and the other third has a rate of 0.5 tons/acre/year. How much sedimentation will the reservoir experience during its 30-year design life?

9.12. Determine the sediment yield from a storm with 80 acre-ft of runoff and a peak discharge of 600 ft^3/sec. The USLE factors for this watershed are 0.3 soil erodibility, 0.5 topographic factor, 0.25 cover management factor, and 1.0 erosion control practice factor.

9.13. Calculate a *C* factor for a farming system in Ohio that has a rotation of corn, soybeans, small grain (oats), meadow, meadow; use conventional autumn tillage. State your assumptions. Compare your answer to the value given in **Table 9.2**.